TIME DOMAIN ELECTROMAGNETIC SURVEYS FOR ASSISTING IN DETERMINING THE GROUNDWATER RESOURCES ON HALEAKALA RANCH PROPERTY ISLAND OF MAUI, HAWAII

Blackhawk GeoSciences Project Number: 3761TNI/400.044

Prepared For:
Tom Nance Water Resources Engineering

Property of TNWRE

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TABLE OF CONTENTS

1.0 INTRODUCTION

This report contains the results of surface Time Domain Electromagnetic (TDEM) geophysical surveys performed for groundwater resource evaluation on the Island of Maui. Blackhawk GeoSciences (Blackhawk) conducted the surveys on June 16 and June 17, 2003, for Tom Nance Water Resources Engineering (TNWRE) and Betsill Brothers Construction (BBC).

TDEM is a geophysical method that determines from the surface the geoelectric section (resistivity layering) of the subsurface. From the geoelectric section, information about geology and water quality can be inferred, because the electrical resistivity of the earth depends on lithology, porosity, and concentration of dissolved solids in the ground water.

The general objective of the TDEM surveys on Maui was to explore for possible basal groundwater occurrences beneath the survey area. These TDEM surveys were conducted near the 600 ft elevation level located above the High Technology Park on Haleakala Ranch property. The locations of the TDEM soundings taken during this survey are shown on Figure 1-1. Geophysical surveys, combined with other hydrogeologic information, are used to provide optimum locations for well placement and well completion depths.

2.0 GEOLOGY/HYDROGEOLOGY

Groundwater resources occur on the Hawaiian Islands basically in two modes:

- In a basal mode where a lens of fresh water floats on saline water, and
- In high-level mode where the fresh groundwater occurrence is controlled by damming structures (i.e. dikes).

The basic geologic and hydrologic framework of the Island of Maui and the two modes of groundwater occurrences are illustrated in Figure 2-1. Fresh groundwater may also occur in areas between these two modes, but production is expected to be highly variable. TDEM surveys previously run on Maui and other Hawaiian Islands have reliably mapped the basal mode water occurrence and the boundary between fresh water in the basal mode and high-level water occurrences.

Basal mode groundwater is resting approximately at sea level near the ocean surrounding the Island of Maui. This is generally due to the fact that the volcanic rocks, which comprise the island, allow rainfall to percolate with little impedance directly downward through the island mass (reference Figure 2-1). The fresh water is assumed to float upon the seawater encroaching from the ocean. Fresh water flows laterally toward the ocean causing the fresh water lens to be thinner at the ocean. When groundwater is under conditions of static equilibrium, the Ghyben-Herzberg Principle states that for every one foot of fresh water above sea level, approximately 40 feet of fresh water will exist below sea level. When at static equilibrium, the transition from fresh water to seawater is generally quite sharp.

TDEM surveys map the resistivity stratification of the subsurface. From numerous previous TDEM surveys and calibration at well sites, characteristic ranges of subsurface resistivities have been derived for the geologic/hydrologic units shown in Figure 2-2. Some overlap in resistivities occurs between different units, however other factors (such as elevation) can be used to separate the units. Therefore the main geologic/hydrologic units that can be derived from TDEM surveys are:

- Depth to seawater saturated volcanics. This occurs in basal mode occurrences, and by using the Ghyben-Herzberg Principle, the thickness of the basal fresh water lens can be computed.
- Dry and fresh water saturated volcanics. These formations generally exhibit high resistivity values. Note that the extent of fresh water saturation is normally based on geographic and elevation information, and that the fresh water cannot be directly detected in the TDEM data.
- Weathered volcanics (laterites) near the surface. These units are generally relatively thin (30 ft to 50 ft) lower resistivity layers that occur at the surface.

Damming structures are inferred with TDEM by distorted soundings, and by soundings that transition between detection of seawater at depth (basal) and soundings that map high resistivities to great depths (high-level).

It is postulated that areas of anomalous basal mode groundwater may be formed by preferential leakage of high-level water into the basal mode over a limited spatial area. These anomalous occurrences are expected to be displayed in the TDEM data by a local increase in the depth to the basal seawater, or by an increase in the basal seawater resistivity (caused by mixing).

3.0 DATA ACQUISITION AND LOGISTICS

A Blackhawk field crew consisting of two geophysicists performed the geophysical surveys. The crew mobilized from Oahu, Hawaii, while the geophysical equipment was shipped to Maui from Golden, Colorado. During the surveys, TNWRE provided project direction and oversight while BBC field personnel helped provide access to the Haleakala Ranch property by a 4WD road. A daily log of field activities during the survey is presented in Table 3-1.

The geophysical equipment utilized for the TDEM surveys was the Geonics EM37 system. The EM37 system consists of a portable motor-generator powered transmitter and PROTEM digital receiver. The main purpose of the TDEM measurements is to derive both the vertical and lateral variations in the geoelectric section. To accomplish this, the TDEM measurements were acquired using a central-loop array at each sounding site. The square transmitter loops were formed by using 12-guage insulated copper wire laid on the ground surface as illustrated in Figure 3-1. The dimensions for the transmitter loops varied between 500 ft by 500 ft to 750 ft by 750 ft. A transmitter is placed at a point in the wire-loop, which drives current pulses through the wire. The transmitter current used in the loops ranged from 14 to 19 amperes. The current pulses induce eddy current flow in the subsurface. A receiver coil positioned in the center of the wire-loop records the decay of the secondary magnetic field due to the eddy currents induced in the subsurface. The effective exploration depth with this type and size array (i.e. 500 ft by 500 ft) is approximately 750 ft, depending upon the ground resistivity and ambient noise (i.e. 60-cycle power line).

The data acquired at each sounding center consisted of measurements at several different receiver gain settings and two transmitter frequencies in order to assure data quality and to obtain data over the largest possible time interval. The data were recorded at base frequencies of 3 Hz and 30 Hz for the EM37. For data quality control, comparisons of offset measurements were made at designated locations near the center of each sounding. The data from each subsequent sounding were stored in a solid-state memory logger in the PROTEM receiver and transferred at the end of each day to a PC for nightly processing. The data acquired during this survey was determined to be of excellent quality with no cultural interferences. A technical note describing the principles of TDEM with case histories is given in Appendix A.

TDEM loop locations were tied to known landmarks (i.e. roads, fences) with a hip-chain and compass. In addition, a hand-held Global Positioning System (GPS) was also used to map the loop locations. During the two days of fieldwork a total of 4 soundings were measured on the Haleakala Ranch property on Maui.

Table 3-1

Daily Log of Field Activities

Date (2003)	Activity
June 12	Receive approval from TNWRE and BBC personnel for groundwater survey on Maui, Hawaii. Mobilize geophysical equipment from Golden, Colorado to Kahului, Hawaii.
June 15	Mobilize Blackhawk crew from Oahu, Hawaii to Kahului, Hawaii.
June 16	Pickup geophysical equipment from Aloha Airlines and Federal Express airfreight and organize into 4WD vehicle for survey. Gain access to Haleakala Ranch property and start geophysical survey. Collect TDEM data on Line 1, Sounding 1 (750 ft by 750 ft loop). Download data to PC in hotel and perform preliminary data analysis.
June 17	Discuss preliminary results with TNWRE personnel. Continue data acquisition on Line 1, Soundings 2, 3, and 4 (500 ft by 500 ft loops). Download data and perform preliminary data analysis at night.
June 18	Discuss results of TDEM survey with TNWRE and BBC personnel; determine that field survey is complete. Pack up and demobilize geophysical equipment from Kahului, Hawaii to Golden, Colorado.
June 19	Demobilize Blackhawk crew from Kahului, Hawaii to Oahu, Hawaii.

4.0 DATA PROCESSING

The TDEM field data collected at the site was transferred nightly from the Geonics PROTEM receiver to a PC for editing and processing. Processing of the TDEM data begins with averaging of the electromotive forces (emf's) recorded at positive and negative receiver polarities. Next, the recordings made at different amplifier gains and frequencies were combined to give one voltage decay curve (transient). The emf's in the various time gates of the decay curves were subsequently entered to an inversion program TEMIXXL (Interpex Ltd.) to obtain a one-dimensional (1-D) geoelectric section that best matches the observed decay curve.

The TEMIXXL inversion program requires an initial model of the geoelectric section measured. The initial model includes the number of layers and the resistivities and thickness for each of the layers. This model is usually derived from general knowledge of the geologic section or from data obtained from drill holes or electric logs. The inversion program is then allowed to adjust these parameters, so that the model curve converges to best fit the field data. The inversion program does not change the total number of layers within the model curve, but allows all other parameters to change freely or they can optionally be fixed constant. To determine the influence of number of layers on the solution, separate inversions with a different number of layers are run. Normally, the model with the fewest number of layers that best fits the field data is used.

An example of the output of the inversion program is shown on Figure 4-1 for Sounding HR-1 on the Haleakala Ranch property. This figure shows the measured data points (in terms of apparent resistivity) superimposed on a solid line on the left panel. The solid line represents the computed forward model for the geoelectric section on the right panel. This geoelectric section is the best match obtained by the inversion program. Figure 4-2 shows the tabulated inversion parameters consisting of measured data, computed data for best match solutions and an example of the table of inversion errors. A three-layer inversion model is shown for Sounding HR-1. The model displays a thin (9 m, 29 ft) surficial layer of clay soil (laterite) with a more resistive (> 600 ohm-m) second layer overlying a third conductive (3.4 ohm-m) layer. The depth to the lower conductive layer is mapped at about 133 ft below sea level (bsl) in this section. The inversion results for each sounding of this project are given in Appendix B.

5.0 INTERPRETATION AND RESULTS

5.1 TDEM Sounding Data

From each TDEM sounding, the reistivity layering (geoelectric section) of the subsurface is derived. The results of the 1-D inversion of the individual TDEM soundings can be linked together (layers with similar resistivities) to create a 2-D geoelectric cross-section along a survey line. For this survey, four soundings were collected along the 600 ft elevation level across the site. This allowed for construction of a single geoelectric cross-section trending from south to north as shown on Figure 1-1. The correlations between geoelectric layers and lithologic units established in Figure 2-2 were used to guide the interpretations on the Haleakala Ranch property.

5.2 Geoelectric Cross-Section Line 1

The layered geoelectric cross-section from the TDEM data taken along Line 1 is shown on Figure 5-1. A three-layer section is interpreted for all soundings on the transect. The upper layer in the geoelectric section exhibits resistivities ranging from 20 ohm-m to 40 ohm-m and is interpreted as a relatively thin laterite surface deposit across the survey area. The thickness of the first layer varies from about 20 ft 30 ft across the site. The second layer in the section is interpreted to represent dry unweathered volcanic layers above sea level (asl) and where it occurs below sea level (bsl) it is expected to be saturated with fresh-brackish basal mode water. The third layer in the cross section with low resistivities (2.9 ohm-m to 3.4 ohm-m) is interpreted to represent salt-water saturated volcanic layers beneath all soundings. The thickness of the fresh-brackish water lens is calculated to be about 133 ft and 135 ft beneath Soundings HR-1 and HR-2, respectively. While, the basal lens is interpreted to be approximately 108 ft to 106 ft thick beneath Soundings HR-3 and HR-4. The difference in the thickness of the fresh-brackish water lens across the survey site is most likely caused by lateral changes in the subsurface volcanic layers and/or permeability differences in these layers.

5.3 Hydrogeologic Interpretations

Table 5-1 contains the approximate thickness of the fresh-brackish water lens calculated from the elevation of the salt-water interface interpreted from the four TDEM soundings taken on the Haleakala Ranch property. The table includes the value of static water level (head) calculated by using the Ghyben-Herzberg Principle.

Table 5-1

Hydrogeologic Information Derived From TDEM Soundings

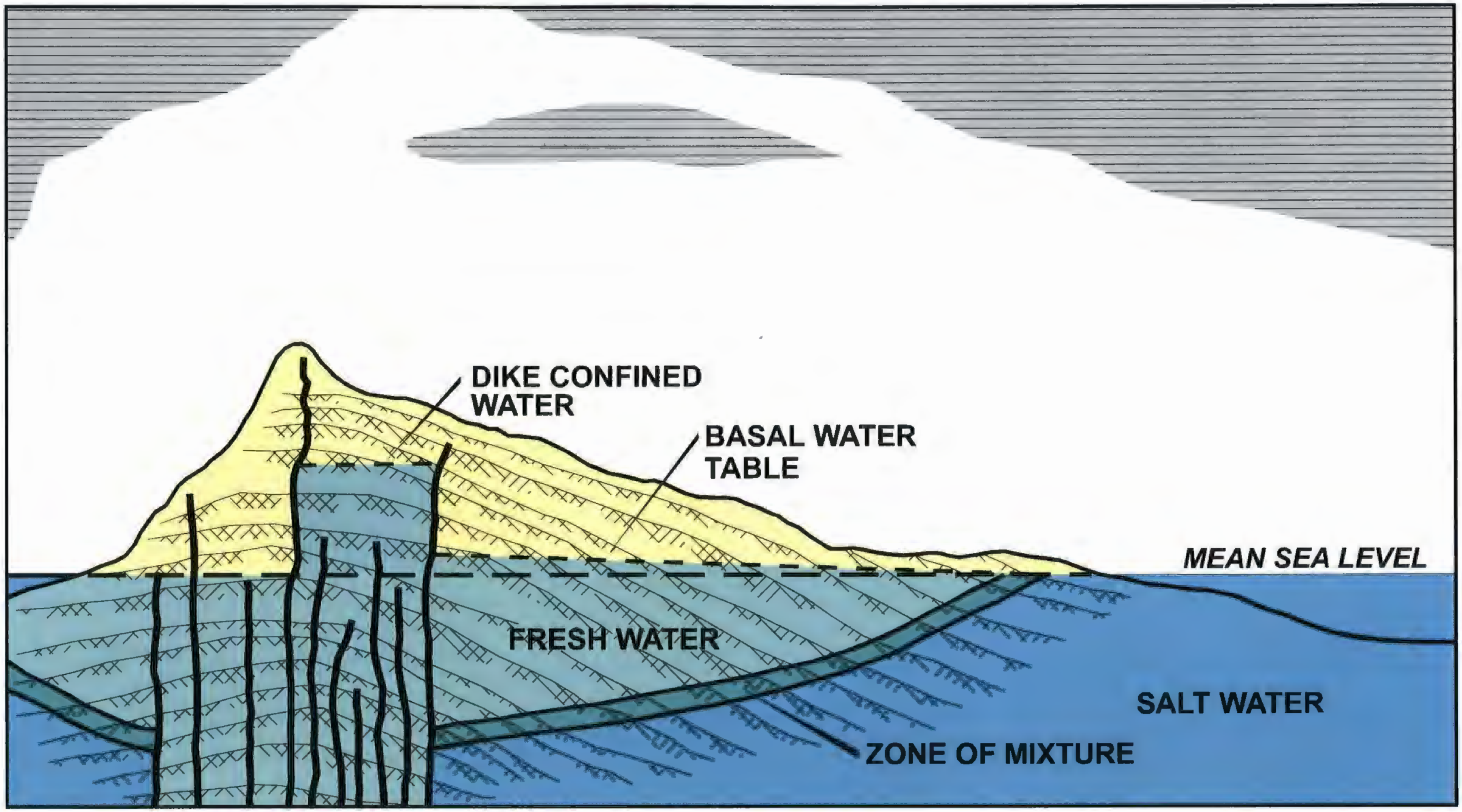
(Values in Feet)

Sounding Number	Surface Elevation	Elevation of Conductive Layer	Calculated Static Water Level (Head)	Approximate Thickness of Fresh-Brackish Water Lens
1	580	-133	3.3	136
2	590	-135	3.4	138
3	580	-106	2.6	108
4	585	-104	2.6	106

6.0 CONCLUSIONS AND RECOMMENDATIONS

The main objective of the TDEM surveys on the Island of Maui was to explore for anomalous basal groundwater resources. The four TDEM soundings taken during this survey were located along the 600 ft elevation level on Haleakala Ranch property above the High Technology Park. The TDEM soundings collected during this survey resulted in the detection of basal groundwater resources beneath all four soundings along the site. The thickness of the fresh-brackish water lens for the geoelectric cross-section was found to vary from approximately 106 ft at Sounding HR-4 on the north end of the line to 138 ft beneath Sounding HR-2 towards the south (reference Figure 5-1 and Table 5-1).

Additional TDEM soundings located both south and east of this survey site would help to define the extent of the basal groundwater lens in this portion of the Island of Maui.



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Schematic Hydrogeologic Cross Section Island of Maui, Hawaii

Tom Nance Water Resources Eng.

Figure No: 2-1

Project No: 3761TNI

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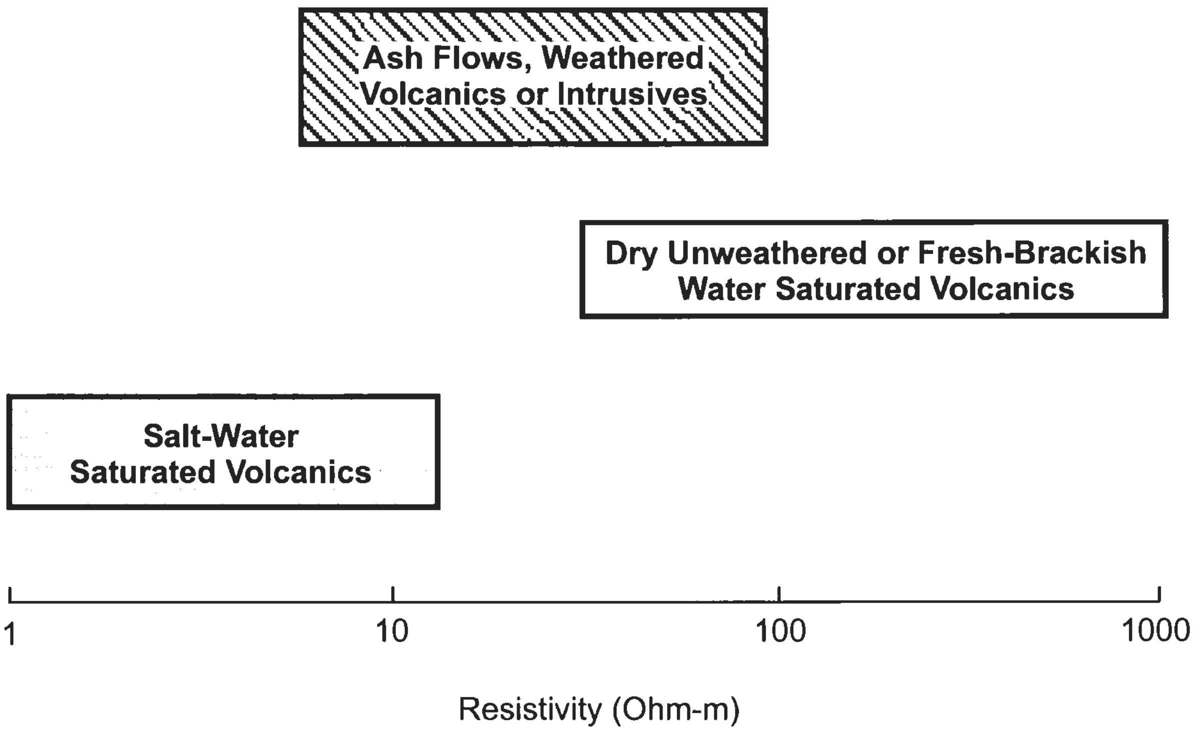

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Characteristic Resistivity Ranges
Haleakala Ranch Property
Island of Maui, Hawaii
Tom Nance Water Resources Eng.

Figure No: 2-2

Project No: 3761TNI

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Explanation

☐ 2 TDEM Transmitter Loops

A—A' Geoelectric Cross-Section

N

MN GN 0°55' 16 MILS 10° 178 MILS

UTM GRID AND 1999 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

0 2000 4000 6000

Scale in Feet

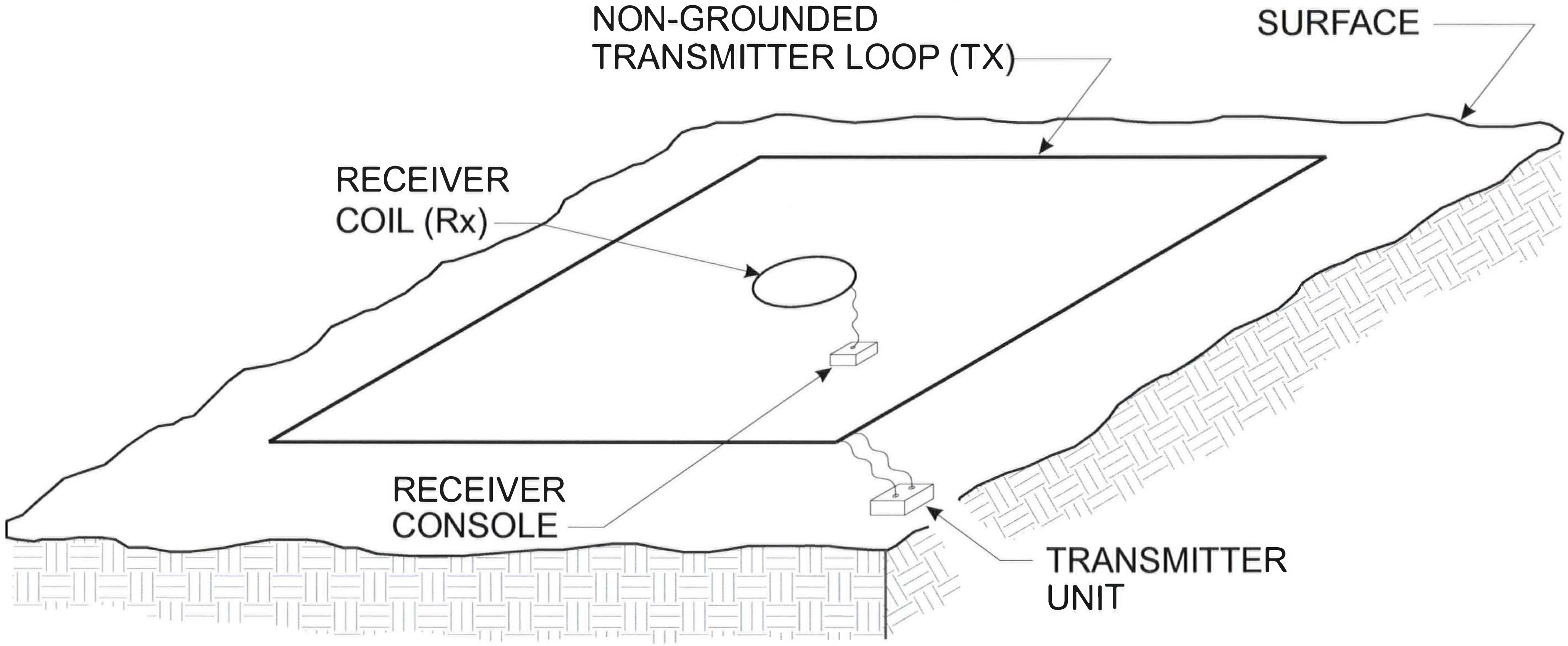
Blackhawk GeoSciences
Golden, Colorado

Sounding Location Map

Haleakala Ranch Property
Island of Maui, Hawaii

Figure No.	1-1
Project No.	3761TNI
File No.	*Path 1 BaseMap.cdr*
Date:	June 2003

Tom Nance Water Resources Eng.



BLACKHAWK GeoSciences a division of Blackhawk GeoServices	**Schematic layout of TDEM system with measurement locations of TX-RX array**	Figure: 3-1
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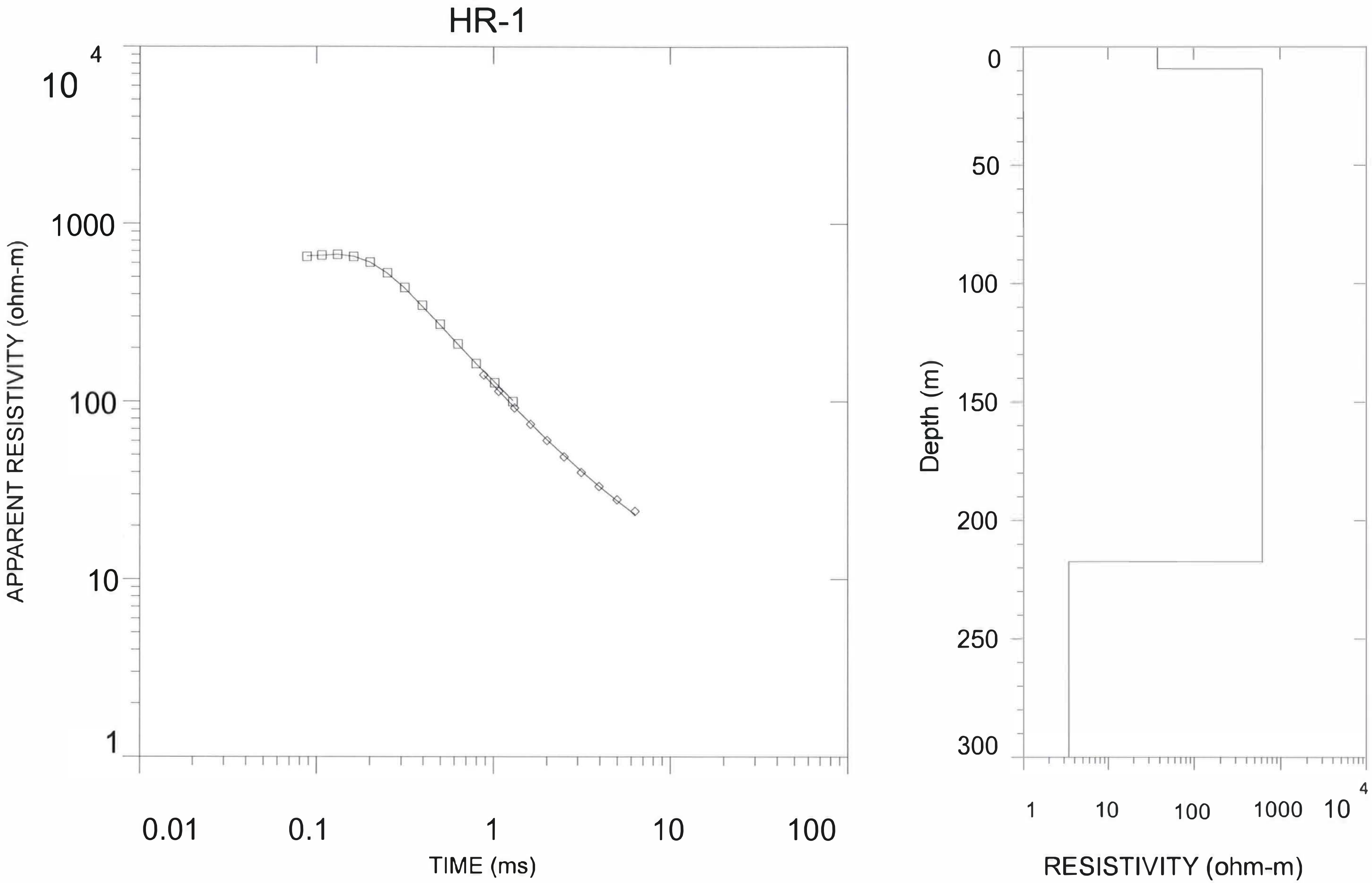

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Sounding HR-1
Example Inversion Output
Apparent Resistivity Curve
Haleakala Ranch Property
Island of Maui, Hawaii
Tom Nance Water Resources Eng.

Figure: 4-1

Project No. 3761TNI

Tdem1.cdr

DATA SET: HR-1

CLIENT: TNWR
LOCATION: Haleakala Ranch Property
COUNTY: Maui
PROJECT: Betsil Brothers Construction
DATE: 06-16-03
SOUNDING: 1
ELEVATION: 177.00 m
EQUIPMENT: Geonics PROTEM
LOOP SIZE: 228.000 m by 228.000 m
AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y)
TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 1.0000 N: 100.0000
SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 1.883 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			177.0	580.0	
1	38.14	9.25	167.7	550.2	0.242
2	616.9	208.3	-40.56	-133.1	0.337
3	3.41				

ALL PARAMETERS ARE FREE

CURRENT: 14.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 3 RAMP TIME: 130.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0881	9472.6	9376.7	1.01
2	0.106	5685.9	5721.8	-0.630
3	0.131	3367.3	3354.6	0.378
4	0.161	2070.1	2064.6	0.265
5	0.200	1357.4	1357.8	-0.0308
6	0.250	954.9	961.4	-0.681
7	0.314	721.5	729.5	-1.10
8	0.395	571.6	586.1	-2.54
9	0.499	463.4	471.9	-1.83
10	0.631	377.7	381.4	-0.968
11	0.799	306.2	308.8	-0.836
12	1.01	245.7	242.5	1.30
13	1.28	194.9	191.5	1.73
14	0.881	299.4	300.9	-0.499
15	1.06	254.4	252.3	0.815
16	1.31	209.8	207.6	1.05
17	1.61	171.2	167.6	2.07
18	2.00	136.8	134.4	1.80
19	2.50	107.7	104.9	2.61
20	3.14	82.82	80.64	2.63
21	3.95	61.19	60.89	0.490
22	4.99	44.34	44.97	-1.43
23	6.31	30.82	32.68	-6.04

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.67				
P 2	0.17	0.20			
P 3	0.02	-0.06	0.84		
T 1	-0.24	-0.21	0.01	0.64	
T 2	0.01	0.02	0.00	0.02	1.00
	P 1	P 2	P 3	T 1	T 2

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Sounding HR-1
Example of Tabulated Data From Inversion
Haleakala Ranch Property
Island of Maui, Hawaii
Tom Nance Water Resources Eng.

Figure: 4-2

Project No. 3761TNI

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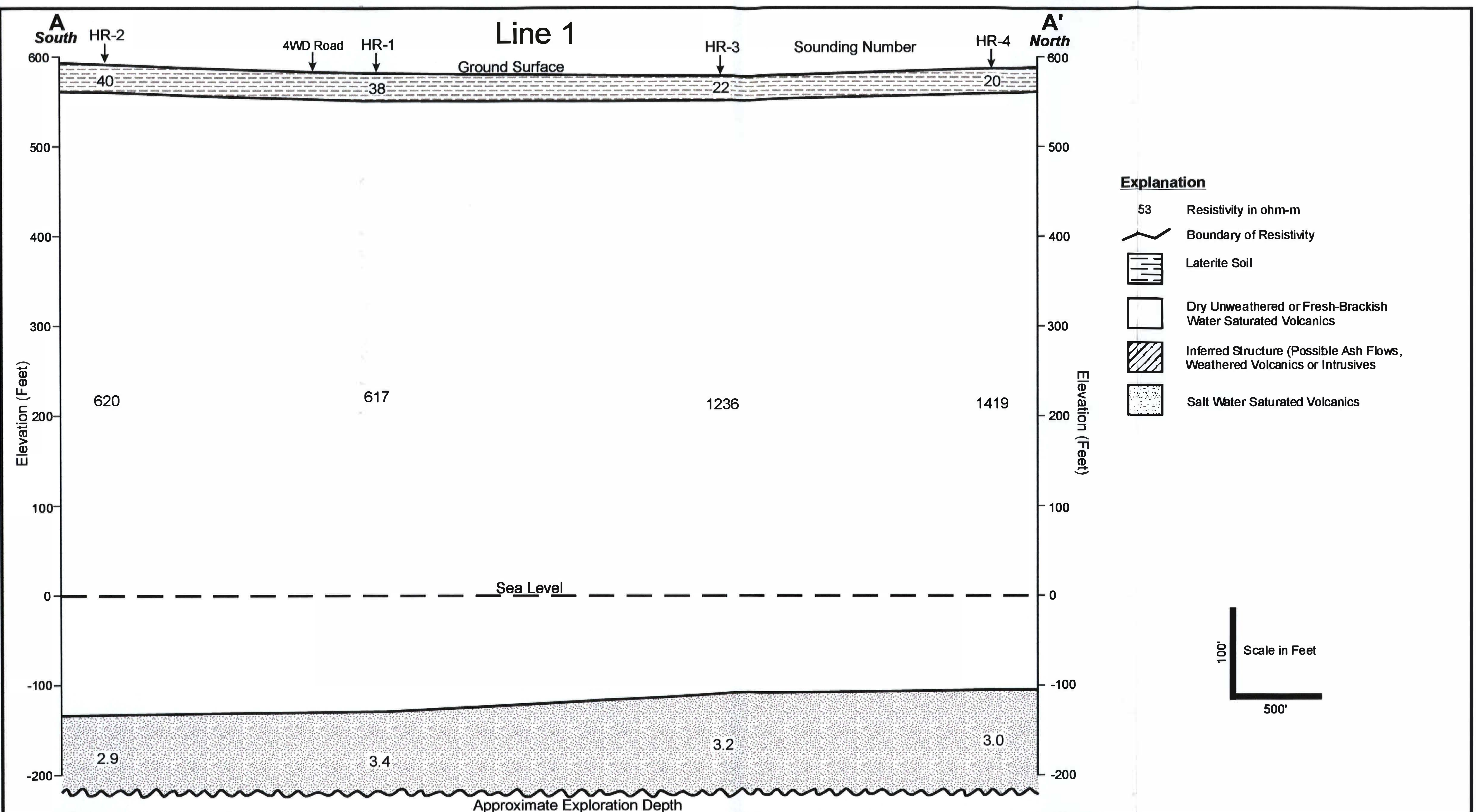

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Geoelectric Cross Section Line 1
From 1-D Inversions
Haleakala Ranch Property
Island of Maui, Hawaii
Tom Nance Water Resources Eng.

Figure No: 5-1

Project No: 3761TNI

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APPENDIX A

TECHNICAL NOTE

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GEOTECHNICAL AND ENVIRONMENTAL GEOPHYSICS

VOLUME II: ENVIRONMENTAL AND GROUNDWATER

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Case Histories of Time-Domain Electromagnetic Soundings in Environmental Geophysics

Pieter Hoekstra and Mark W. Blohm**

Abstract

Time-domain electromagnetic (TDEM) soundings are a surface electromagnetic technique that finds increasing use in environmental geophysics. Commercial equipment is now available for TDEM soundings in the exploration depth range from about 5 m to about 5000 m. Application of TDEM is illustrated in three case histories.

The transmitter-receiver array used in all three investigations was the central-loop array, in which measurements of the electromotive force due to the vertical magnetic field are made with a receiver in the center of square, nongrounded transmitter loops. The dimensions of the transmitter loops were varied from 30 m by 30 m for effective exploration depths between 5 m to 75 m, to 500 m by 500 m for effective exploration depths to about 2500 m. These relatively small dimensions of receiver/transmitter arrays, compared to the exploration depth, allow TDEM surveys to be made in urban areas where open spaces are limited in size, and where environmental and ground-water problems are perhaps most urgent. Also, the procedures of signal processing used in TDEM facilitate operation in the presence of high ambient electrical noise prevalent in urban settings.

The three case histories map:

(1) the depth of first occurrence of brine for assisting site evaluation of a high-level nuclear-waste repository in bedded salts near Carlsbad, New Mexico,

(2) the encroachment of salt water in a multiple-zone coastal aquifer system in the Salinas Valley, California, (The availability of about 100 monitoring wells allowed correlation of formation resistivities to ground-water salinity.) and

(3) shallow basalt flows in the exploration depth range from 5 m to 30 m. (This case history shows the results of TDEM measurements over the time range from about 10^{-6} s to 10^{-4} s with central-loop soundings of small (30 m) dimensions.)

Introduction

Time-domain electromagnetic (TDEM) soundings increasingly are being employed for determining geoelectrical sections. Reported applications of this TDEM method are in mapping of volcanic cover (Frischknecht and Raab, 1984; Keller et al., 1984), onshore and offshore permafrost (Ehrenbard et al., 1983), geothermal reservoirs (Fitterman et al., 1988), hydrocarbons (Rabinovich et al., 1977; Wightman et al., 1983), and ground water (Fitterman and Stewart, 1986; Mills et al., 1988). Theoretical aspects of the method, such as behavior of magnetic and electric fields (e.g., Nabighian and Oristaglio, 1984), definition of apparent resistivity (Kaufman and Keller, 1983; Spies and Eggers, 1986), transmitter-receiver arrays (Kaufman and Keller, 1983), and influence of two-dimensional (2-D) and three-dimensional (3-D) structures on one-dimensional interpretations (Hohmann, 1988; Newman et al., 1987) are discussed throughout the geophysical literature [see also McNeill, Vol. I—Ed.].

Several reasons are apparent for the increasing use of TDEM in environmental geophysics. In urban areas ambient electrical noise is high, and open spaces limited. TDEM surveys can often work around these limitations. Small transmitter-receiver arrays can be laid out in athletic fields, parks, and other open spaces, and ambient

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electrical noise due to residential power service can often be removed by stacking. Also, recent availability of equipment with fast, current ramp turn-off and early-time measurements bring shallow mapping objectives for ground-water protection and contaminant investigations within the exploration depth range of TDEM.

A limitation of TDEM at this time is the lack of practical, cost-effective algorithms for interpreting 2-D and 3-D structures. At present, forward modeling of 2-D and 3-D structures (Newman et al., 1987), requires significant central processing unit (CPU) time on the mainframes negating their application to shallow TDEM exploration. It is in the development of practical algorithms for 2-D and 3-D interpretations for personal computers that the main advances in TDEM must come.

Illustrated applications of the method to three environmental objectives include (1) assisting in siting of high-level, nuclear-waste repositories, (2) mapping the intrusion of salt water in coastal aquifers, and (3) mapping the thickness of thin basalt flows. The basic principles of the equipment and the procedures of data acquisition and processing are similar for all three case histories. Some characteristics of central-loop array measurements, such as land survey requirements, location of plotting points, and vertical resolution are reviewed briefly. Equipment design parameters and data acquisition, processing, and interpretation procedures are discussed. These principles are illustrated subsequently on the three case histories. The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories.

Practical Aspects of Data Acquisition

Transmitter-Receiver Arrays

The three types of transmitter-receiver arrays employed in TDEM soundings are illustrated in Figure 1. The array used in the three case histories is the central loop array (Figure 1b). For applications in environmental geophysics there are certain advantages to the central loop array, such as:

(a) Land survey and space requirements.—Figure 2 shows the measured behavior of the electromotive forces (emf's) due to horizontal (x) and vertical (z) magnetic field components on a profile through the center of a square transmitter loop at 2.2 ms after current turn-off. Data at other times would show a similar behavior but differ in amplitudes. The emf due to the z-component can be seen to be relatively flat about the center. Location errors of $\pm 10\%$ L (L is side of square) cause negligible errors, and deviations from a square transmitter loop have little effect on a data set. Because in central loop soundings the geoelectric section is derived from emf$_z$, requirements for accurate positioning are minimal which enhances the practical value of field survey productivity, and allows flexibility in choosing a station location. Because emf$_x$ has a zero crossing in the center of the loop, its measurement would require careful survey control. Also, ambient electrical noise is higher in horizontal components.

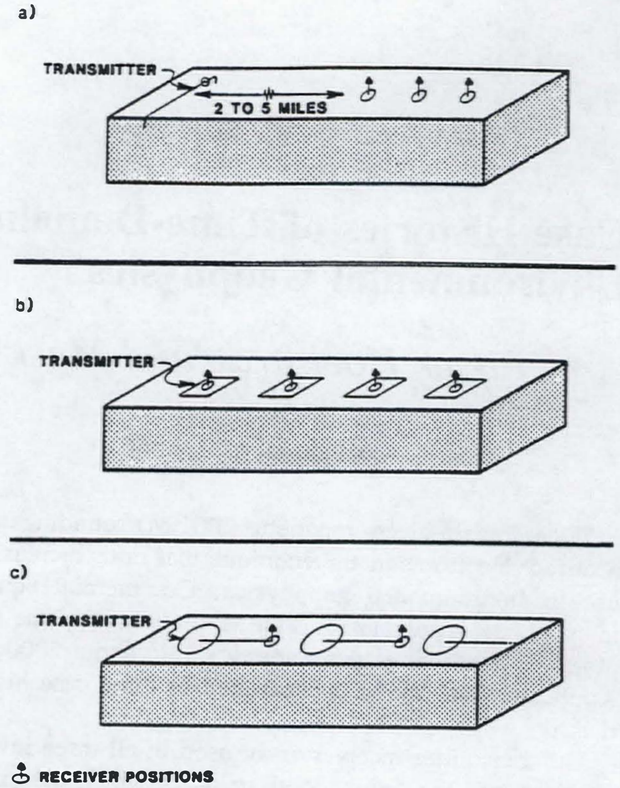

FIG. 1. Transmitter-receiver arrays, (a) grounded line, (b) central loop, and (c) loop-loop.

The dimensions of transmitter loops in central-loop arrays depend on required exploration depth, exploration objective, and geoelectric section. Optimum dimensions are generally selected from forward modeling and field tests. Typically, the length of a side of the transmitter loop is about two-thirds of the exploration depth for the EM-37. The EM-42 is generally employed for exploration depths from about 300 m to 2500 m with 500 m by 500 m transmitter loops, and with a grounded line array for deeper objectives.

The grounded line array (Figure 1a) with long offset receiver locations is dominantly used in deep electrical soundings in support of oil and gas exploration (Keller et al., 1984). The loop-loop array (Figure 1c) finds ap-

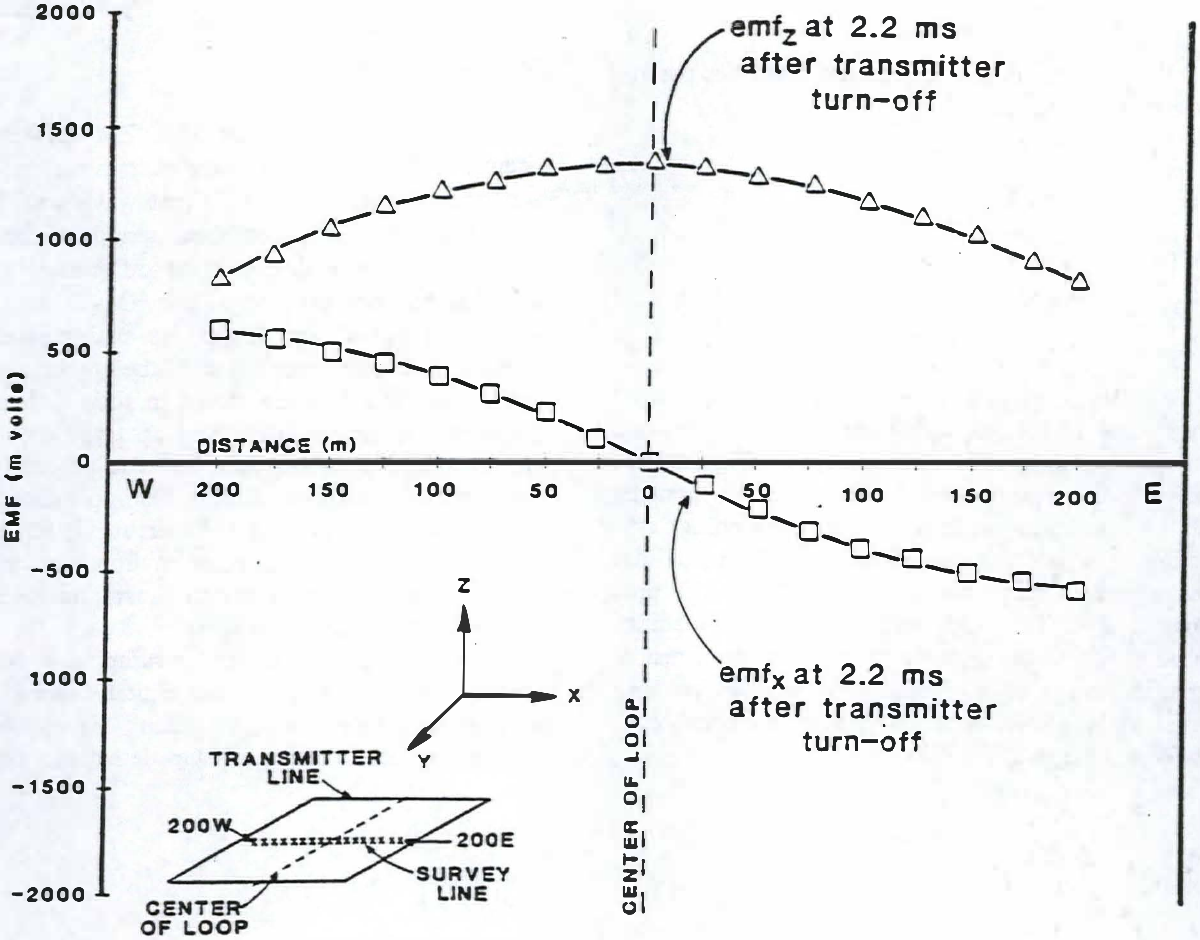

FIG. 2. Measured behavior of the electromotive forces due to vertical (emf$_z$) and horizontal (emf$_x$) magnetic fields on a profile through the center of a square transmitter loop.

plication in mineral exploration and in mapping of fractures and shear zones.

(b) Well-defined sounding plotting points.—The behavior of induced eddy currents and the resulting behavior of the secondary magnetic fields in horizontally-layered media are well documented (Kaufman and Keller, 1983; Ward and Hohmann, 1988). They show a current distribution diffusing downward and outward from the source. For nongrounded, square-loop transmitters currents are symmetrically distributed about the center. Therefore, the center is a well-defined plotting point.

In the grounded-line array or loop-loop array the entire section between transmitter and receiver is expected to influence the measurements, although subsurface conditions near the receiver may have a larger influence on emf$_z$ measured. The correct plotting point of a station is not well defined. Some place the plotting point below the receiver (Keller et al., 1984) and others midway between the transmitter and receiver (Rabinovich and Surkov, 1978). This same situation prevails in loop-loop arrays. In frequency-domain loop-loop arrays the midpoint of the array has traditionally been used as the plotting point.

(c) Vertical resolution.—Kaufman and Keller (1983) show that (1) the asymptotic behavior of emf$_z$ at late time, is given by

$$\mathrm{emf}_z = \frac{\mu^{5/2}}{4\pi^{3/2}} \frac{\sigma^{3/2} M_t M_R}{t^{5/2}}; \tag{1}$$

where

t = time after current turn-off,
σ = conductivity of uniform half-space,
μ = magnetic susceptibility,
M_t = moment of transmitter,
M_R = moment of receiver;

and (2) that this asymptotic expression describes the emf over the time range given by;

$$\frac{\tau}{R} > 16, \tag{2}$$

where

$$\tau \text{ is } \sqrt{\frac{8\,\pi^2 t}{\mu_0\,\sigma}}.$$

Figure 3 is a nomograph showing the onset of "late stage" behavior ($\tau/R > 16$), as a function of resistivity, and time at several values of R. Also shown on Figure 3 are the time ranges of measurement for the three systems used in the case histories. In central loop soundings typical values of R are between 15 m and 250 m, so that over a large time range of measurements emf_z is proportional to $\sigma^{3/2}$. This high sensitivity of the quantity measured (emf_z) to the geoelectric section often results in a reduced range of equivalence for certain sections compared to other electrical and electromagnetic techniques (Fitterman et al., 1988).

Equipment

The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories. All three sets of equipment use the current waveform illustrated in Figure 4, consisting of equal periods of time-on and time-off. Figure 5 illustrates the difference in data acquisition between the EM-47 and EM-37, and the EM-42. In the EM-47 and EM-37 an analog stack is performed, and after completion of the stacking and A/D conversion, the data are stored in solid state memory. Normally, at the completion of a survey day, the data are transfered to a computer for data processing, plotting, and interpretation. During field operations no real-time processing is available. Minimum detectable signal in typical, urban, ambient-noise environments is 10^{-9} V/A-m^2 (normalized by current in transmitter loop, and effective area of receiver coil).

In the EM-42 the transient is sampled at 400 μs intervals, and these samples are digitally stored on 1/2-inch, 9-track tape. "Smart stacking" is applied to the data in real time. The minimum detectable signal with

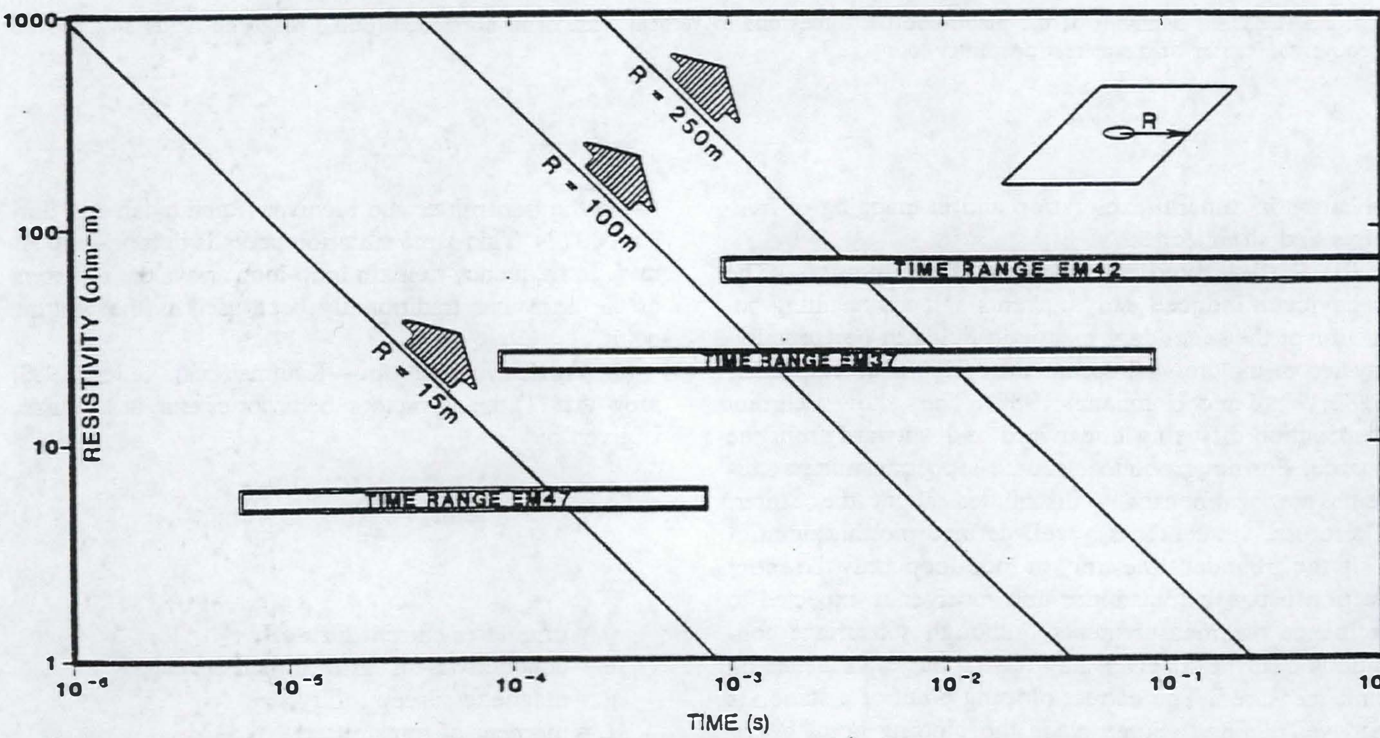

FIG. 3. Nomograph showing onset of late stage behavior for central-loop array as a function of time and resistivity of uniform half-space.

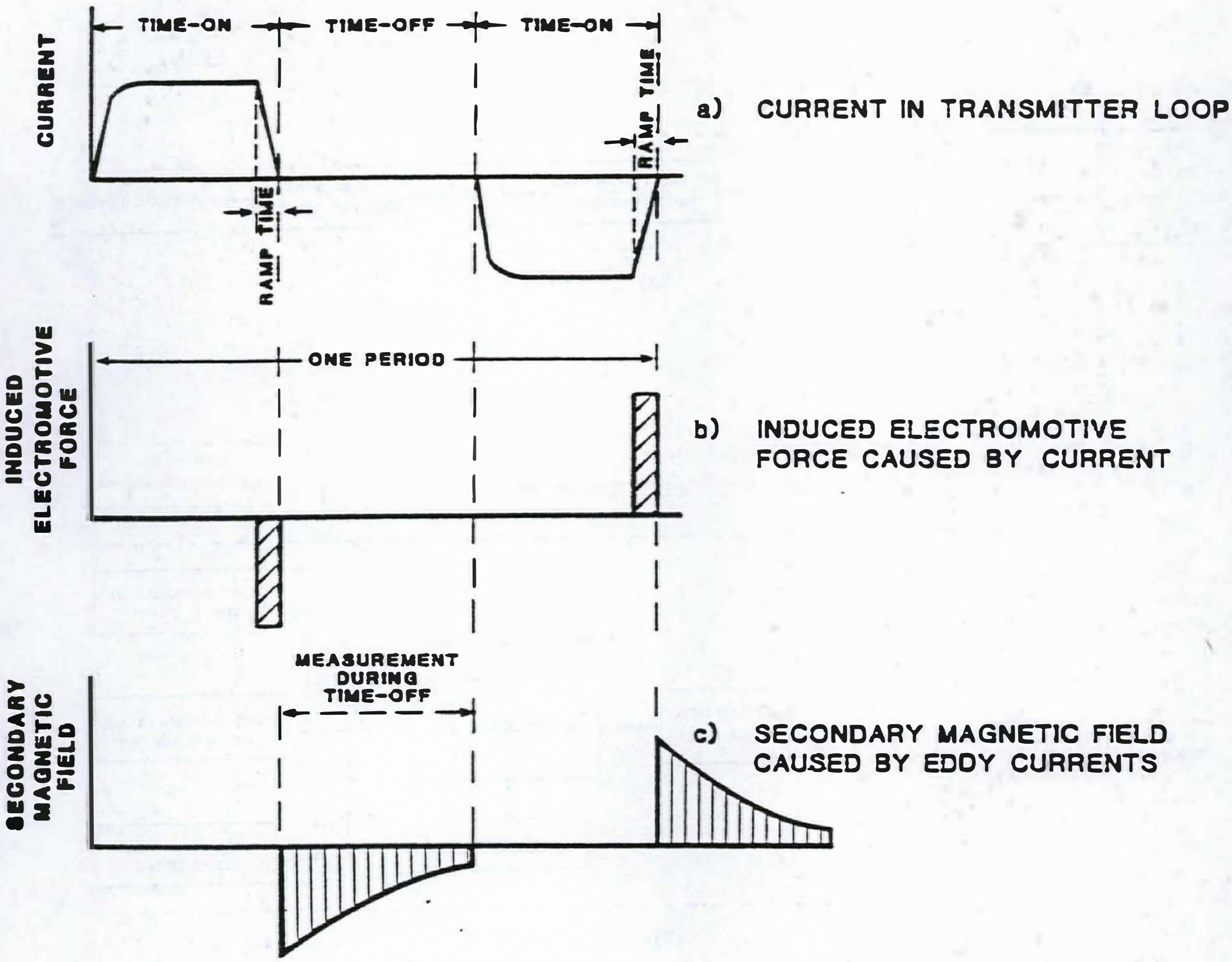

FIG. 4. System waveforms employed in Geonics EM-47, EM-37, and EM-42.

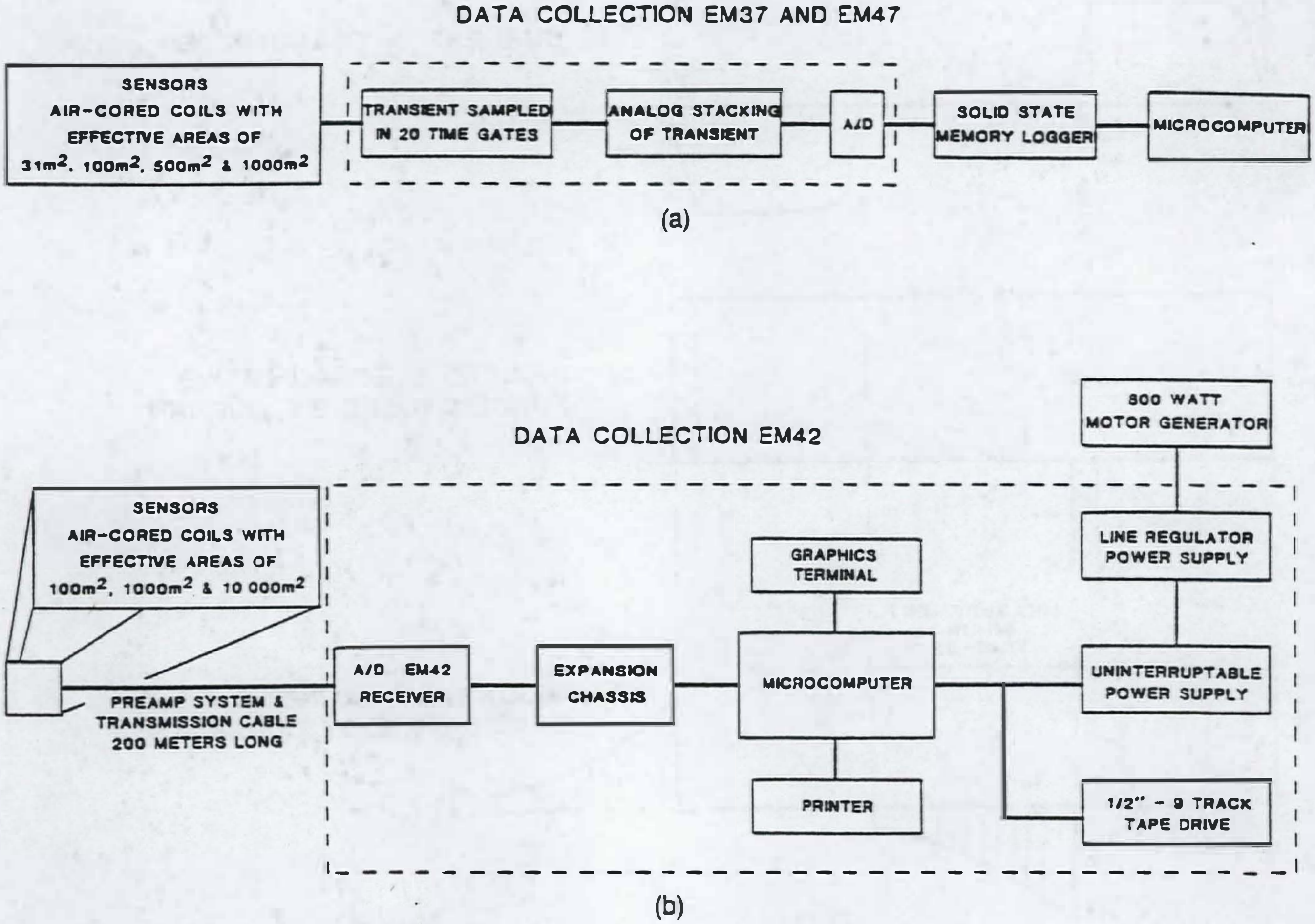

FIG. 5. Block diagrams of TDEM systems.

the EM-42 in typical ambient noise environments is 10^{-12} V/A-m^2

Data Acquisition

Recording transient decays with central loop soundings requires a large dynamic range, because emf$_z$ decays as $t^{-5/2}$, as shown in equation (1). This large dynamic range is often obtained by acquiring a data set in segments using different combinations of base frequencies, gains, and air coil receivers. An example of such a data set is given in Figure 6. The early time part of the curve was acquired at a base frequency of 3 Hz, 100 m^2 air coil and EM-37 receiver; the later time section was recorded with the EM-42 receiver, a 10 000 m^2 air coil and a base frequency of 0.075 Hz. When the 10 000 m^2 coil is used, the early time segment of this curve is purposely saturated. It is common to collect data sets at two receiver polarities, various gain settings, base frequencies, and with receiver coils of different effective areas. These various data sets are combined in one transient-decay curve that is subsequently entered into inversion routines.

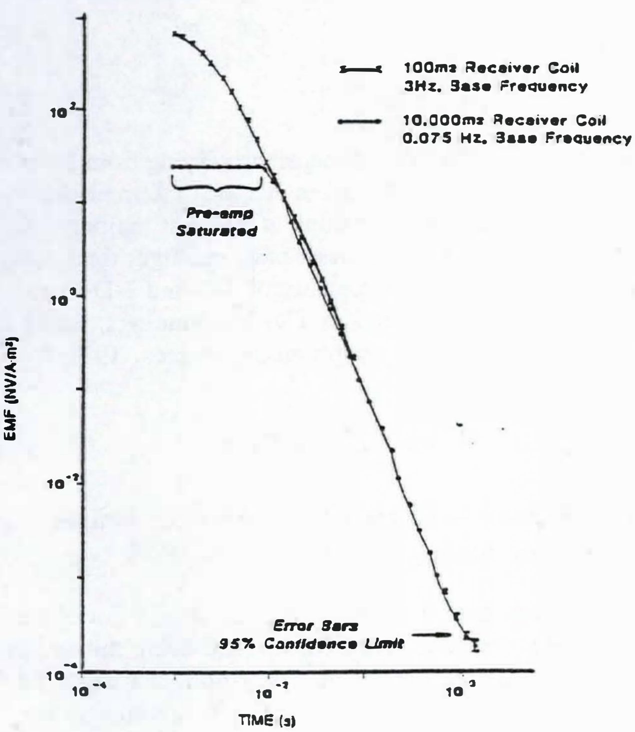

FIG. 6. Emf$_z$ measured in center of 500 m by 500 m transmitter loop.

Definition of Apparent Resistivity

All electrical and electromagnetic methods commonly transform the voltages or emf's measured into apparent resistivities. In TDEM several definitions of apparent resistivity are in use (Kaufman and Keller, 1983; Goldman, 1988) and the merits and pitfalls of the various definitions have been reviewed in Spies and Eggers (1986). These pitfalls are often avoided by (1) integrating inversions with available geologic data, and (2) using albums of forward-model curves for first-guess solutions. In all the case histories late-stage (Kaufman and Keller, 1983) apparent resistivity curves are used. Two reasons for that selection were (1) over a large range of time late-stage behavior is observed in central-loop soundings, and (2) extensive volumes of late-stage model curves (Goldman and Rabinovich, 1974) are available.

Data Interpretation

All the examples shown in the case histories were interpreted by one-dimensional (1-D) inversions of the data using a ridge-regression inversion program (ARRTI, Interpex Ltd, 1985). The input for the program are the emfs measured in various time gates, certain equipment and survey parameters (transmitter loop size, current, ramp time, receiver coil effective area), and number of layers to be used in the inversion. Also, an initial solution is entered. Goldman (1988) discussed the dependence of inversion routines on this first guess. To mitigate convergence to unrealistic solutions, first guesses are made to correspond with known geologic conditions, and depending on the quality of available geologic information, certain parameters in a geoelectric section may be fixed at specific values, e.g., as observed in borehole logs.

In TDEM soundings there is merit in carefully considering inversion errors at each time gate, because each section of the curve is often diagnostic of a certain depth section (Kaufman and Keller, 1983; Raiche and Gallagher, 1985). This can be illustrated by a central loop TDEM sounding with a 500 m by 500 m transmitter loop over a Tertiary valley fill in Nevada. Figure 7b shows the late-stage, apparent resistivity curve and Figure 7a two 1-D inversions for this sounding. The difference between the two inversions is the absence of a resistive layer (basalt flow) in section 1, and its presence in section 2. Figure 7c shows the error between the measured data and the two inversions. The increased error over the early time range suggested inserting an additional layer into the inversion. The existence of this resistive layer has been confirmed by drilling.

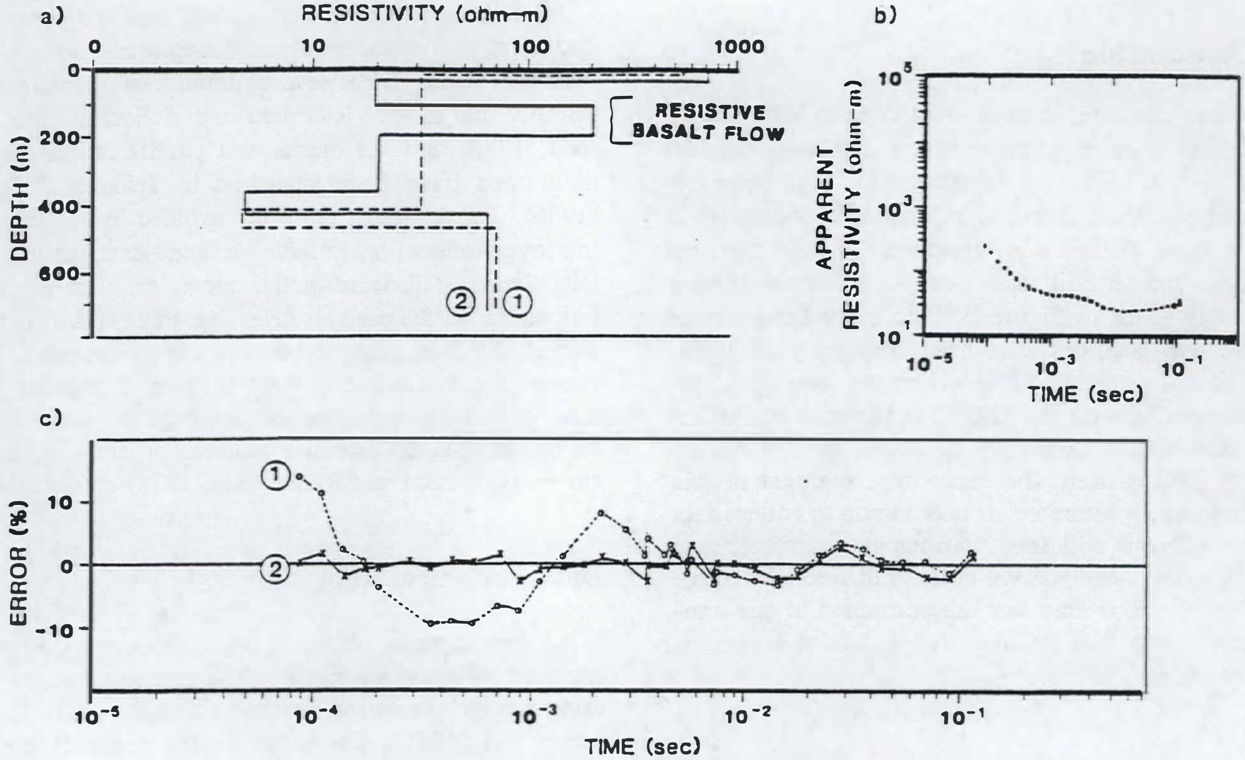

FIG. 7. Geoelectric sections (a) derived from 1-D inversions of measured apparent resistivity curve (b) over Tertiary Valley fill in Nevada. For each geoelectric section error of inversion is shown as function of time (c).

Validity of One-Dimensional Interpretation

The complexity of evaluating the influence of 2-D and 3-D structures of TDEM data is often cited as a disadvantage (Goldman, 1988). Indeed, currently, computations of 2-D and 3-D structures require computations that cannot be economically and practically applied in routine exploration programs. From the 2-D and 3-D computations (Newman et al., 1987) that have been published, important conclusions can be derived about the validity of 1-D interpretations in the presence of 2-D and 3-D structures. For example, Newman et al. (1987) computed the response over a resistive and conductive 3-D structure buried in a layered half-space at a depth of about 300 m. They reached the conclusion that 1-D inversions gave good estimates of the depth of burial of the 3-D structure, but unreliable depth extent and resistivities of the 3-D body. They used relatively large transmitter loops (1000 m by 1000 m) compared to exploration depth (1000 m) in their computations.

Drill-hole control is seldom sufficient to evaluate thoroughly the influence of 2-D and 3-D structures on a data set. Our experience, based on several thousand soundings with transmitter loop dimensions varying from 30 m by 30 m to 500 m by 500 m, is that 1-D interpretations yield good depth interpretations in the vast majority of work undertaken. Nevertheless, practical algorithms for data interpretation in the presence of 2-D and 3-D structures is an important need in TDEM soundings. Some efforts in that direction are promising (James, 1988).

Case Histories

Case History—High Level Nuclear Waste Repository Siting

The storage panels of the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico are being mined in the bedded salts of the Salado formation at a depth of about 600 m below ground surface. Underlying the Salado formation is the Castile formation, which is composed primarily of anhydrite and halite. It is known from oil and gas drilling that the Bell Canyon formation, underlying the Castile formation, can contain brines (Barrows et al., 1982).

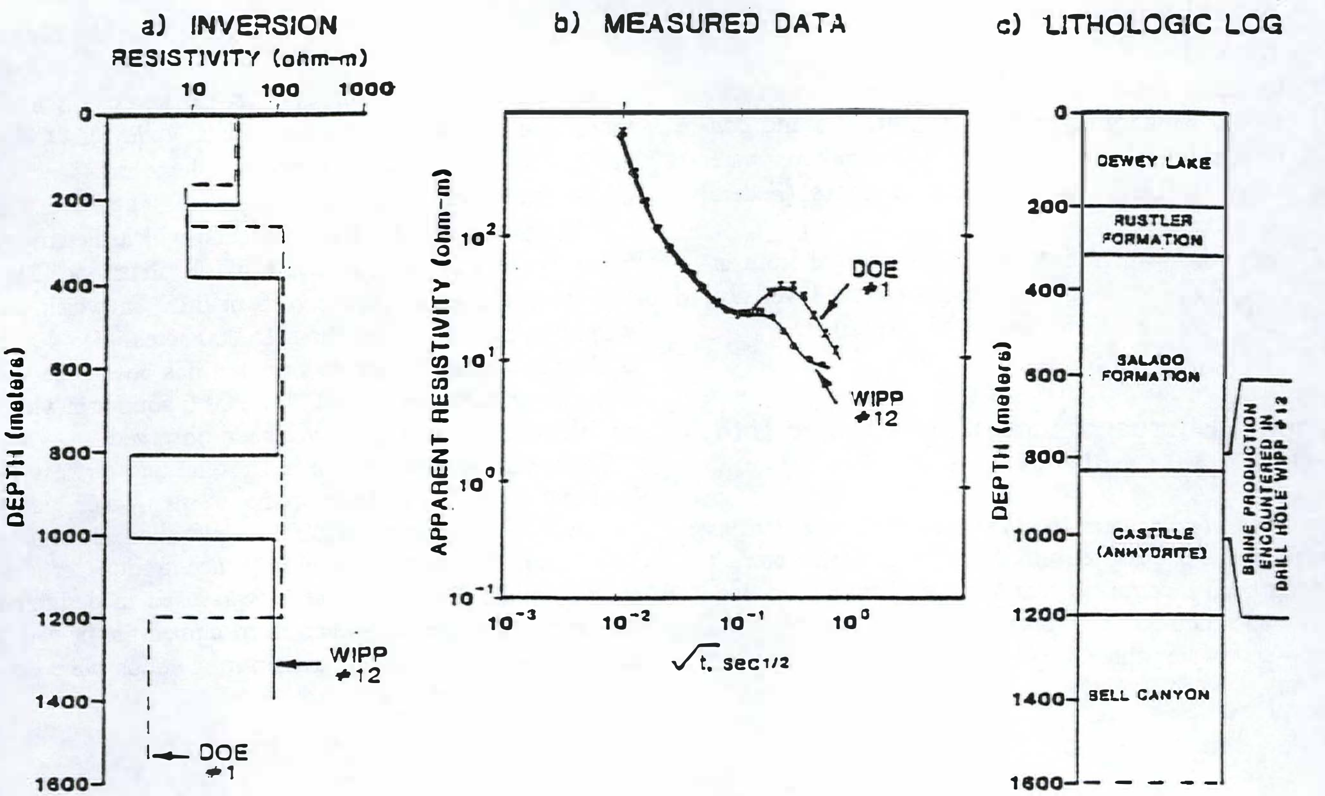

FIG. 8. Two measured late-stage apparent resistivity curves (b) and corresponding geoelectric sections derived from 1-D inversions (a). Also shown is a lithologic log common to both sounding locations (c).

The concept for placing a high level nuclear waste (HLW) repository in bedded salts at 600 m is to exploit the low hydraulic permeabilities of overlying bedded salts, and underlying anhydrites and halites. However, in the general vicinity of Carlsbad, New Mexico, drill holes encountered pressurized brine reservoirs at depths between 730 m and 915 m in the Castille formation (Register, 1981). The objective of TDEM surveys was to map the depth of first occurrence of brine over the waste storage panel and surrounding area.

A TDEM survey was conducted on a 500 m grid using central loop TDEM soundings over the waste storage panels and at selected drill hole locations. The transmitter loop dimen ions employed were 500 m by 500 m and the TDEM equipment used was the Geonics EM-42.

Figure 8b shows two apparent resistivity curves located within 150 m of two drill hole locations, WIPP #12 and DOE #1. The resistivity layering derived from 1-D inversions for these two soundings is given in Figure 8a., and Figure 8c shows a lithologic log common to WIPP #12 and DOE #1. In the drilling of WIPP #12, brines were encountered at a depth of 850 m, and in drill hole DOE #1 no brines were encountered to total depth (TD = 900 m). The depth of first occurrence of brine observed in WIPP #12 is in excellent agreement with the depth of the low resistivity layer derived from the 1-D inversion of the adjacent TDEM sounding. Depth of occurrence of the low resistivity layer derived from the TDEM inversion near drill hole DOE #1 is at 1200 m, some 300 m below TD, and at a depth corresponding to the Bell Canyon formation.

The 1-D inversions of TDEM soundings over the waste storage panels showed first depth of occurrence of brine below 1050 m. This depth generally corresponds to the Bell Canyon formation. Thus, the 1-D interpretations of the depth of first occurrence of brine were consistent with available ground truth. A major concern remains the minimum dimensions of brine occurrences detectable with central loop soundings. This problem is being addre sed by 2-D and 3-D forward modeling.

There are several other important objectives in environmental geophysics for mapping depth of first occurrences of brine, such as:

(1) Siting injection zones for oil field brines, and other liquid waste injection wells. Regulations require

injection zones to have a concentration of dissolved solids greater than 10 000 ppm and confining zones must separate US drinking water supplies (USDW) and injection zones (Federal Register, 1987).

(2) Monitoring migration of wastes upward from injection zones along fractures, abandoned wells, or faulty casings (Fitterman et al., 1986).

Mapping Encroachment of Salt Water Into Fresh-Water Aquifers

Intrusion of salt water in coastal aquifers often has as its main cause excessive withdrawal of ground water. It has long been recognized that surface electrical or electromagnetic methods can be effective in mapping fresh water—salt water interfaces (Flathe, 1964). Here, the application of TDEM surveys for this purpose is illustrated by a case history from the Salinas Valley, CA (Mills et al., 1988). A schematic hydrogeologic cross-section of the study area is given in Figure 9. There are four aquifer zones (1) a perched aquifer in which the ground water is heavily contaminated by fertilization, (2) a 180 ft aquifer approximately 60 m thick in which salt water has intruded under about 15 000 acres, (3) a 400 ft aquifer in which salt-water intrusion has been observed under about 6600 acres, and (4) a 900 ft aquifer in which no salt-water intrusion has yet been observed.

Thus, salt-water intrusion has progressed farthest inland into the 180 ft aquifer, so that to map water quality in the 400 ft aquifer requires exploration through a 180 ft aquifer containing high concentrations of dissolved solids. This information was used in designing the survey. To map salt-water encroachment in the 180 ft aquifer 100 m by 100 m transmitting loops were em-

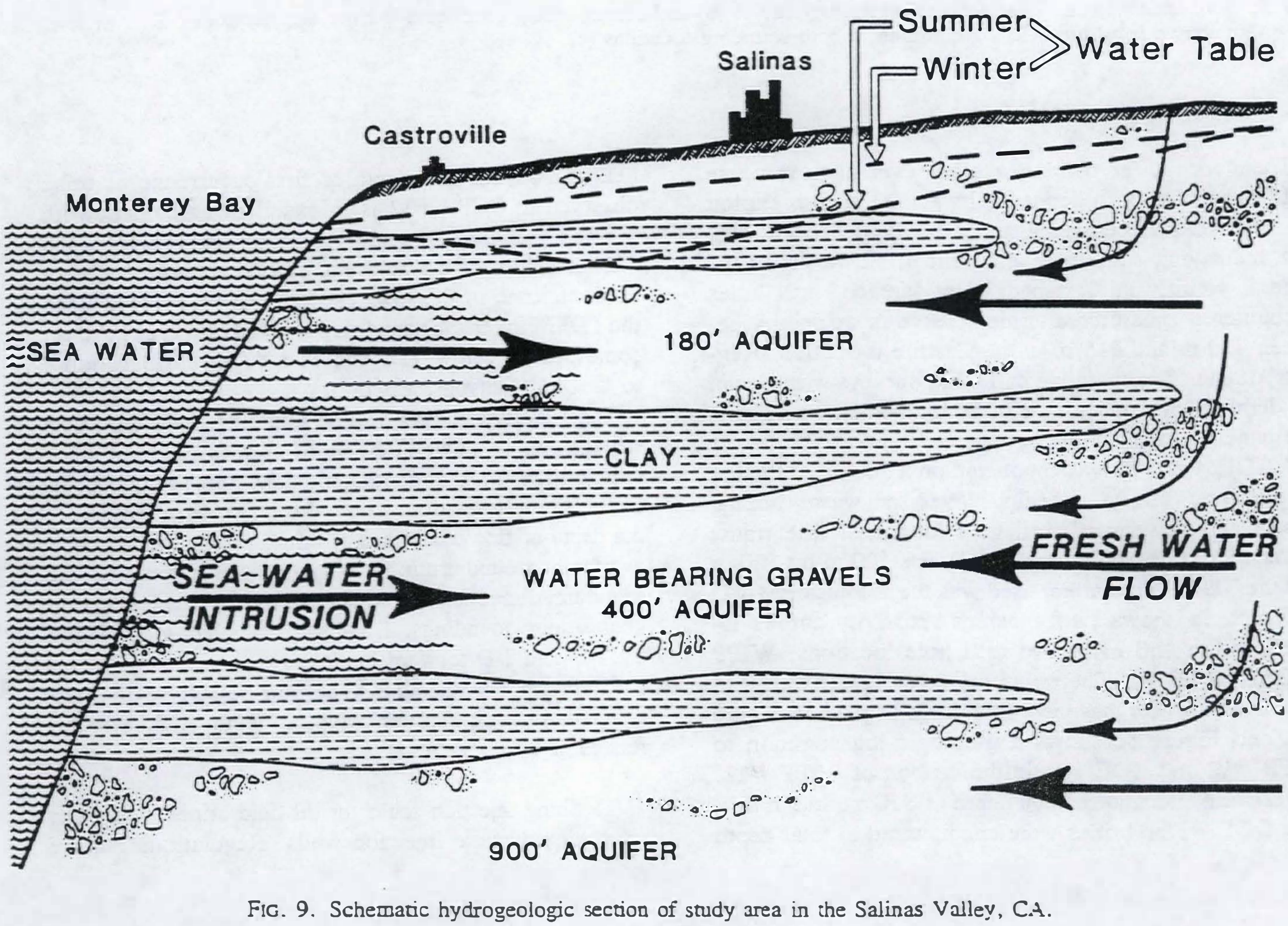

FIG. 9. Schematic hydrogeologic section of study area in the Salinas Valley, CA.

ployed. These transmitting loop dimensions provided sufficient field strength to derive the resistivity variation in the 180 ft aquifer. Larger transmitting loop dimensions (200 m by 200 m) were employed for exploration in the 400 ft aquifer. Approximately 100 stations were measured.

A series of four late-stage apparent-resistivity curves along cross-section B-B′ (Figure 12) are shown on Figure 10 along with geoelectric sections derived from 1-D inversions. Figure 11 shows the geoelectric section derived from TDEM soundings along profile B-B′. In the 180 ft aquifer the resistivity gradually increases inland from 1.5 $\Omega \cdot m$ (station L24/3) to 18 $\Omega \cdot m$ (station L10/1). In the 400-ft aquifer the resistivity increased from 6.0 $\Omega \cdot m$ to in excess of 20 $\Omega \cdot m$.

Information from monitoring wells maintained by the Monterey County Flood Control and Water Conservation District was used to help constrain the number of layers used for the inversions of the TDEM data, and to correlate formation resistivities with equivalent chloride concentration. Correlation of formation resistivities with chloride concentration showed that a resistivity of approximately 8 $\Omega \cdot m$ corresponds to a 500 ppm chloride concentration. Figure 12 shows the surface projection of the 500 ppm isochlor contours (8 $\Omega \cdot m$ formation resistivity) in the 180 ft and 400 ft aquifers. The 500 ppm isochlor, based on monitoring wells, is also shown. There is more detail in the contours derived from the TDEM surveys mainly because of the higher station density.

These types of TDEM surveys have now been performed in several areas of Florida (Steward and Gay, 1981), Massachusetts (Fitterman and Hoekstra, 1982), California (Mills et al., 1988), and New York. Important advantages of TDEM soundings in these surveys are:

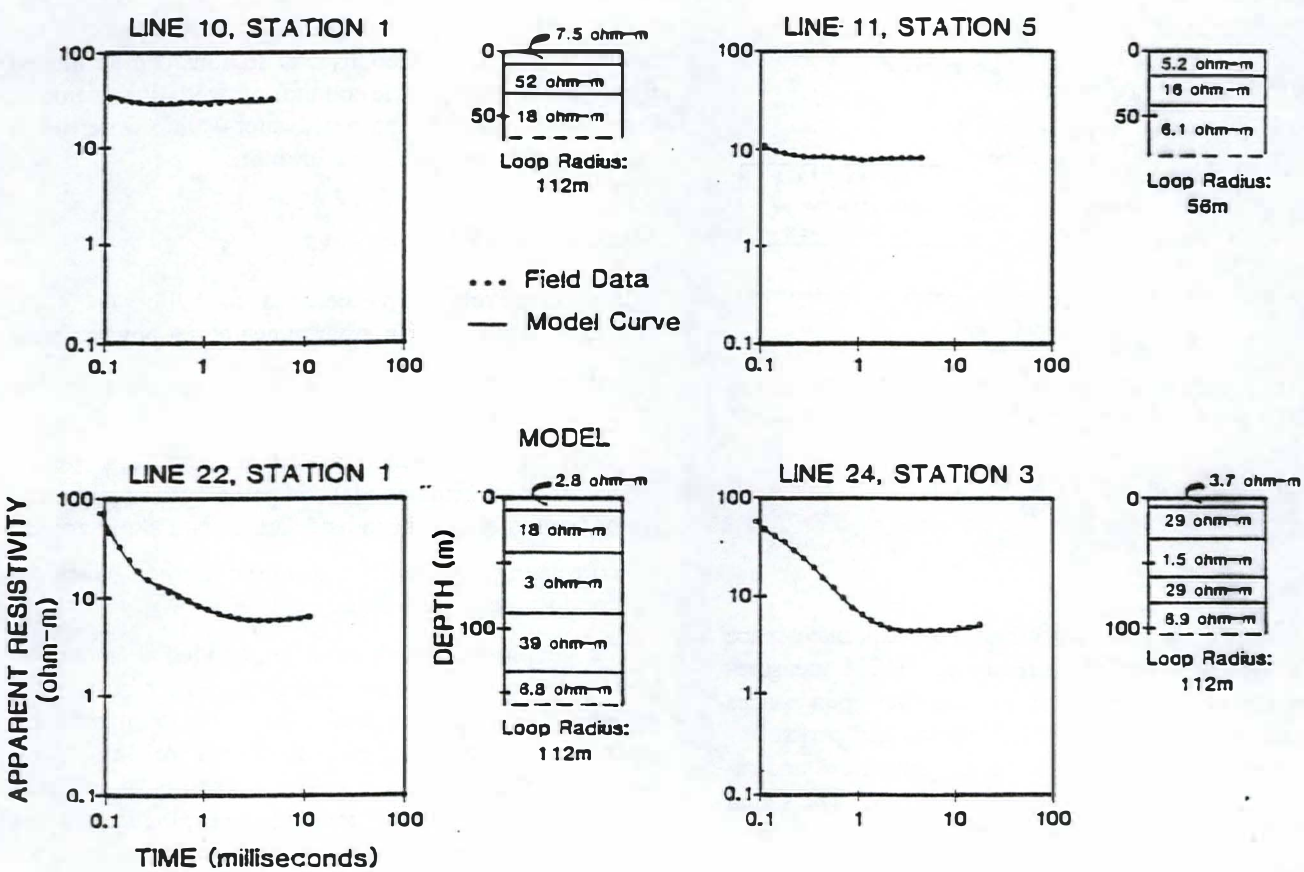

FIG. 10. Four apparent resistivity curves and inverted geoelectric sections along section B-B′ (Figure 12).

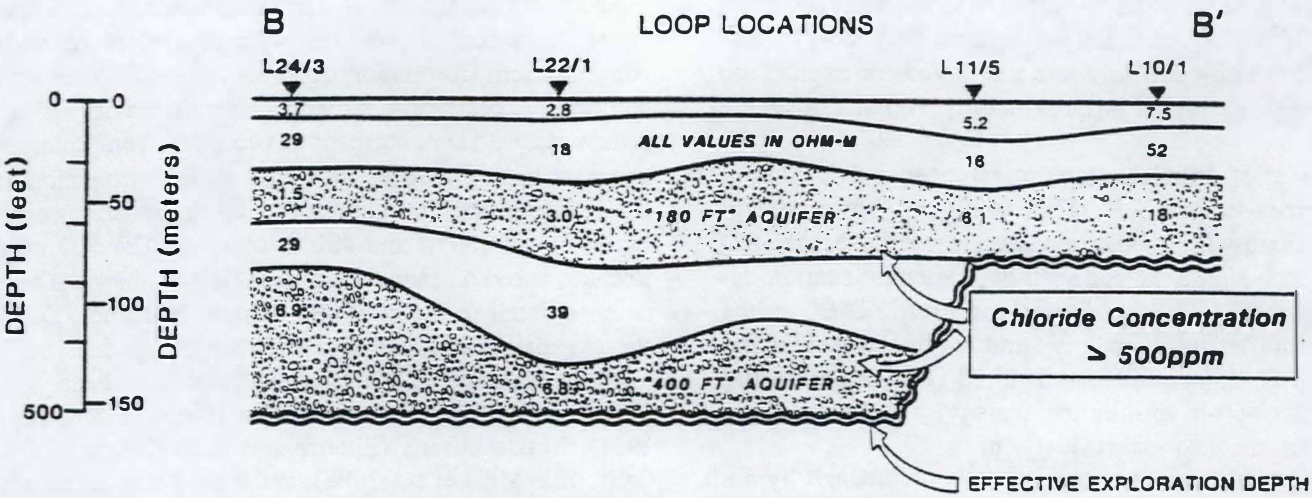

FIG. 11. Geoelectric section B-B' derived from TDEM soundings.

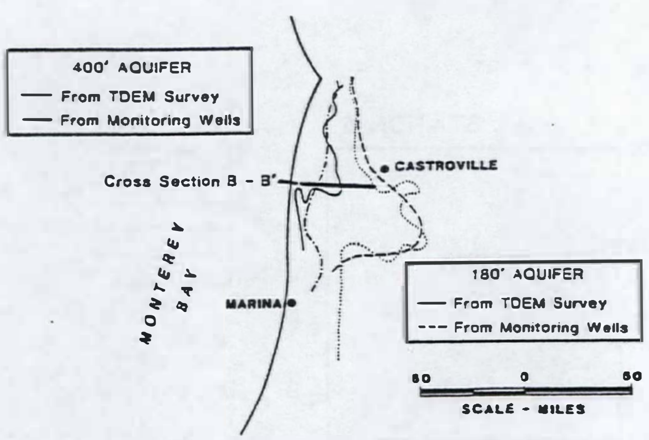

FIG. 12. Comparison of position of 500 ppm isochlor in 180 ft and 400 ft aquifers derived from monitoring wells and TDEM soundings.

(1) Coastal areas are often urbanized and limited space is available for measurements. TDEM measurements were often made in available open spaces such as high school athletic fields and parks.

(2) Ambient electrical noise (e.g., powerlines and radio stations) is high in developed areas. The signal stacking used in TDEM has proven an effective way for recovering signal from noise.

The utility of TDEM surveys for water management plans are in (1) providing optimum location for placement of monitoring and production wells, (2) determining depth of completion of such wells, (3) interpolating the position of the fresh water–saline water interface between wells, and (4) monitoring the movement of the interface over time. Geophysical stations can be moved from year to year, while monitoring wells lose some of their usefulness once the fresh water–saline water interface has migrated past their locations.

Shallow TDEM Surveys

Important exploration objectives for shallow (< 50 m) electrical exploration in environmental geophysics are

mapping continuity of confining layers, such as clay lenses;

mapping the presence of contaminants (e.g., originating from brine ponds) and pathways for migration of contaminants, such as fractures and shear zones;

correlating hydraulic transmissivities to electrical conductance (e.g., Huntley, 1986).

The geophysical methodologies applied to these exploration problems have mainly been dc resistivity soundings (e.g., Evans et al., 1982) and frequency-domain electromagnetic conductivity profiling (e.g., McNeill, 1982). With the recent availability of a TDEM system (Geonics EM-47) for shallow exploration, some of these objectives are now within the exploration depth range of TDEM. An example of shallow central-loop soundings with a prototype EM-47 is a survey over relatively thin basalt flows near Golden, Colorado.

On North and South Table Mountain in Golden, Colorado, lava flows overlie the Denver formation. Figure 13a shows the geologic section of the upper 100 m on North Table Mountain (Waldschmidt, 1939). Figure 13c shows an apparent resistivity curve measured in the center of a 30 m by 30 m transmitter loop with the EM-47 and its 1-D inversion. A peak current of 2 A was driven through the loop, and the ramp turn-off (Figure 4a) was 2.5 μs. The first time gate was centered at 6.4 μs and data were collected at base frequencies of 300 Hz and 30 Hz. The geoelectric section derived from the 1-D inversion (Figure 13b) shows good agreement between geologic boundaries and breaks in resistivity.

For this geoelectric section and for 30 m by 30 m transmitter loops (R = 15 m), late stage commences at about 10^{-5} s (Figure 3), so that almost the entire measured curve is in late-stage. Also shown on Figure 13c are forward modeled curves with different thicknesses of the upper basalt flow, while all other parameters were held constant. Large changes in the curves occur mainly

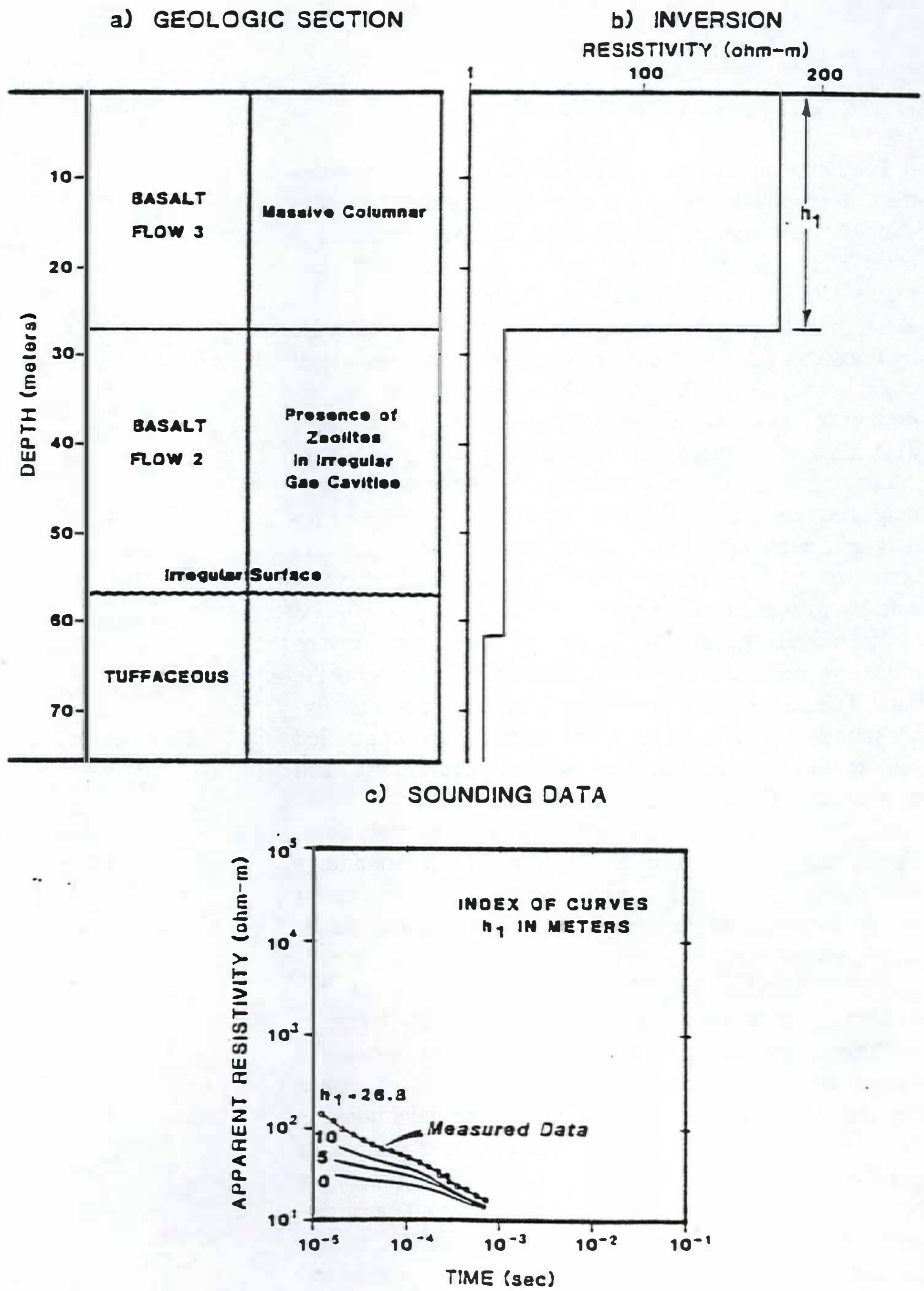

FIG. 13. (a) Geologic section of North Table Mountain, Golden, CO; (b); and geoelectric section derived from 1-D inversion of central loop sounding data with 30 m by 30 m transmitter loop; (c) the measured apparent resistivities are superimposed on a series of forward model curves in which the thickness of the upper basalt layer is varied.

over the time range from 10^{-5} s to 10^{-3} s; the time range covered by EM-47 measurements.

The conclusions from a number of conducted surveys is that the EM-47 can be employed in the depth range from 5 m to 75 m, depending somewhat on the geoelectric section. Since transmitter loop dimensions of 30 m by 30 m can be employed, survey productivity is high (30 to 50 stations per day). The TDEM EM-47 promises to be an effective methodology for electrical mapping in environmental geophysics, particularly in urban areas where space is limited and ambient noise is high.

Discussion

Focusing on the use of TDEM methods in environmental geophysics is such a narrow focus that there is a danger of overstating the utility of TDEM, compared to other electrical and electromagnetic measurement techniques. Raiche et al. (1985) and Fitterman et al. (1988) show that the range of equivalence in some geoelectric sections can in principle be reduced by combined use of dc resistivity and TDEM soundings. It is, therefore, important to note that the exploration objective in all three case histories consisted of determining depth to a conductive stratum, objectives optimally suited for electromagnetic techniques. TDEM surveys and other electromagnetic techniques have limitations for detecting thin resistive strata, and such limitations are readily evaluated by forward modeling.

One advantage of TDEM not evident from forward modeling computations is the absence of scatter in the data. The data scatter frequently observed in dc resistivity soundings, and distant source techniques (controlled source audiomagnetotelluric, audiomagnetotelluric, and magnetotelluric methods) are often due to lateral variation in resistivity and measurement of the electric field. The scatter is reduced in central loop TDEM soundings mainly because of the short source/receiver separation and measurement of the time derivative of magnetic fields. The apparent resistivity curves shown in these investigations are typical of a large number of stations. No smoothing of the data is performed before inversions.

The recent availability of a shallow TDEM system for the exploration depth range from 5 m to 75 m makes this technique suitable for such environmental studies as well-site protection programs, and mapping plumes of ground-water contamination. Contamination plumes are often confined to narrow zones, and the high lateral resolution possible with shallow central loop TDEM soundings allows definition of both the lateral and vertical extent of such plumes.

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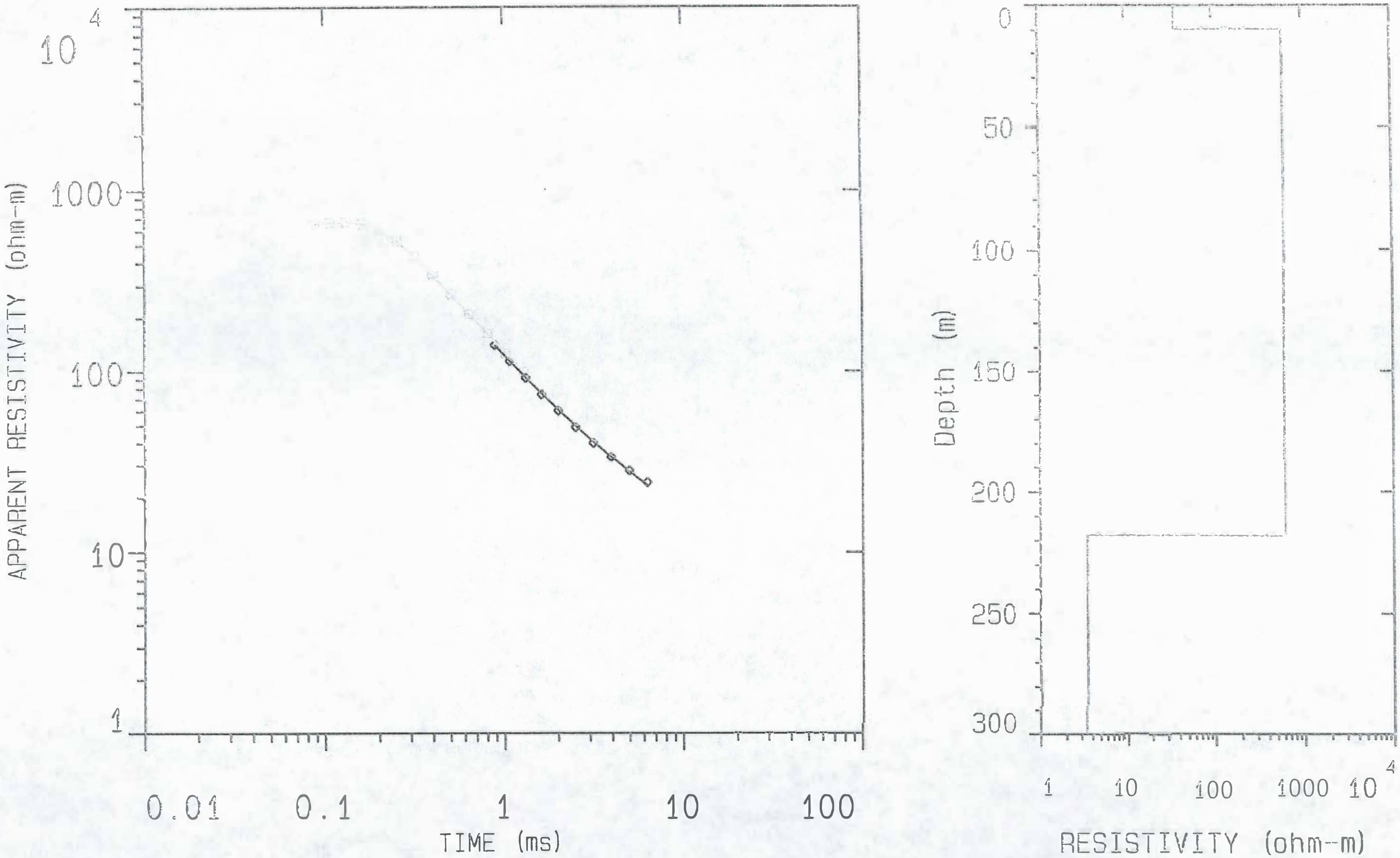
APPENDIX B

TIME DOMAIN ELECTROMAGNETIC SOUNDING CURVES AND DATA PRINTOUTS

Prepared For:

TOM NANCE WATER RESOURCES ENGINEERING

HR-1



APPARENT RESISTIVITY (ohm-m)
10^4
1000
100
10
1
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
50
100
150
200
250
300
1
10
100
1000
10^4
RESISTIVITY (ohm-m)

DATA SET: HR-1

CLIENT: TNWR
LOCATION: Haleakala Ranch Property
COUNTY: Maui
PROJECT: Betsil Brothers Construction
DATE: 06-16-03
SOUNDING: 1
ELEVATION: 177.00 m
EQUIPMENT: Geonics PROTEM
LOOP SIZE: 228.000 m by 228.000 m
AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y)
TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 1.0000 N: 100.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 1.883 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(ft)	CONDUCTANCE (Siemens)
			177.0	580.0	
1	38.14	9.25	167.7	550.2	0.242
2	616.9	208.3	-40.56	-133.1	0.337
3	3.41				

ALL PARAMETERS ARE FREE

CURRENT: 14.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 3 RAMP TIME: 130.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0881	9472.6	9376.7	1.01
2	0.106	5685.9	5721.8	-0.630
3	0.131	3367.3	3354.6	0.378
4	0.161	2070.1	2064.6	0.265
5	0.200	1357.4	1357.8	-0.0308
6	0.250	954.9	961.4	-0.681
7	0.314	721.5	729.5	-1.10
8	0.395	571.6	586.1	-2.54
9	0.499	463.4	471.9	-1.83
10	0.631	377.7	381.4	-0.968
11	0.799	306.2	308.8	-0.836
12	1.01	245.7	242.5	1.30
13	1.28	194.9	191.5	1.73

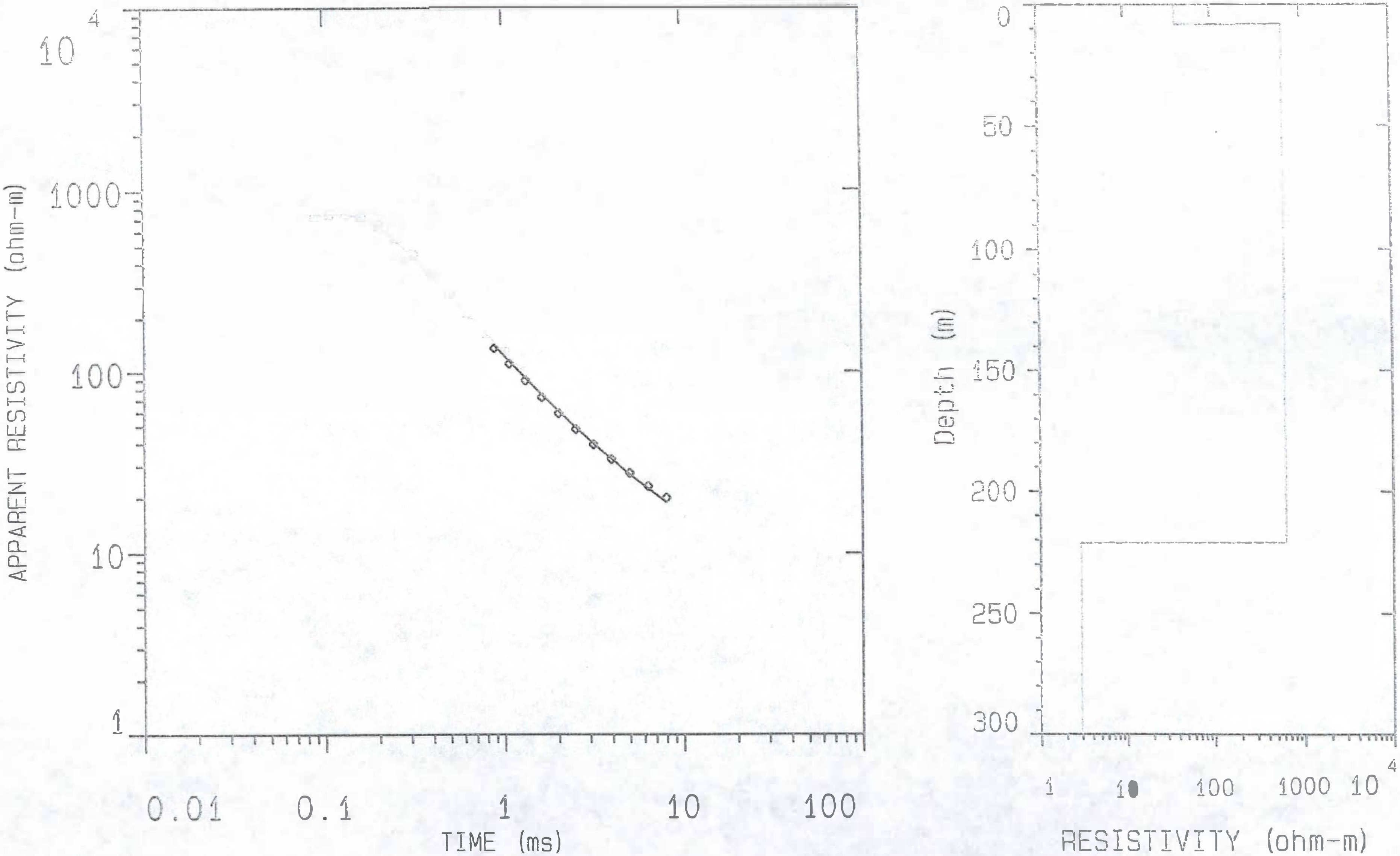
CURRENT: 14.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 130.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	0.881	299.4	300.9	-0.499
15	1.06	254.4	252.3	0.815
16	1.31	209.8	207.6	1.05
17	1.61	171.2	167.6	2.07
18	2.00	136.8	134.4	1.80
19	2.50	107.7	104.9	2.61
20	3.14	82.82	80.64	2.63
21	3.95	61.19	60.89	0.490
22	4.99	44.34	44.97	-1.43
23	6.31	30.82	32.68	-6.04

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.67				
P 2	0.17	0.20			
P 3	0.02	-0.06	0.84		
T 1	-0.24	-0.21	0.01	0.64	
T 2	0.01	0.02	0.00	0.02	1.00
	P 1	P 2	P 3	T 1	T 2

HR-2


APPARENT RESISTIVITY (ohm-m)
TIME (ms)
Depth (m)
RESISTIVITY (ohm-m)

DATA SET: HR-2

CLIENT: TNWR
LOCATION: Haleakala Ranch Property
COUNTY: Maui
PROJECT: Betsil Brothers Construction
DATE: 06-17-03
SOUNDING: 2
ELEVATION: 180.00 m
EQUIPMENT: Geonics PROTEM
LOOP SIZE: 152.000 m by 152.000 m
AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y)
TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 2.0000 N: 100.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 3.911 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(ft)	CONDUCTANCE (Siemens)
			180.0	590.6	
1	40.07	8.23	171.7	563.3	0.205
2	620.2	212.9	-41.19	-135.2	0.343
3	2.94				

ALL PARAMETERS ARE FREE

CURRENT: 19.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 3 RAMP TIME: 125.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0881	4890.6	4775.8	2.34
2	0.106	2901.1	2880.9	0.695
3	0.131	1724.6	1716.8	0.447
4	0.161	1072.9	1096.7	-2.21
5	0.200	729.3	743.6	-1.96
6	0.250	534.2	569.4	-6.57
7	0.314	416.1	444.0	-6.70
8	0.395	335.8	341.7	-1.74
9	0.499	272.6	280.1	-2.75
10	0.631	222.8	225.5	-1.22
11	0.799	180.5	184.1	-1.99
12	1.01	144.3	145.4	-0.801
13	1.28	115.2	115.0	0.242

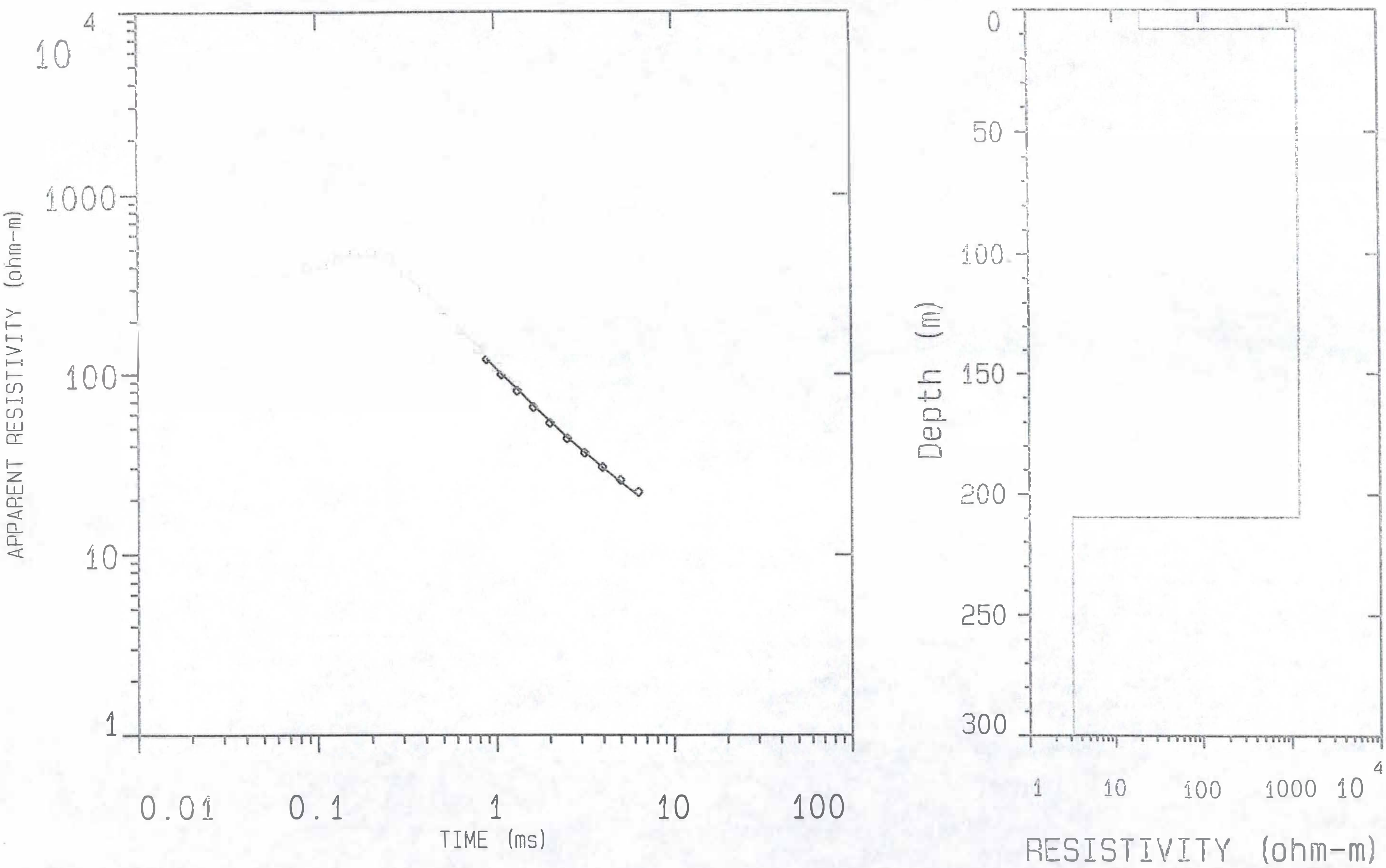
CURRENT: 19.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 125.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	0.881	191.6	181.6	5.19
15	1.06	159.8	151.8	5.01
16	1.31	132.2	125.8	4.83
17	1.61	107.7	102.1	5.25
18	2.00	86.09	82.23	4.48
19	2.50	66.89	64.56	3.48
20	3.14	50.96	50.08	1.73
21	3.95	38.30	37.84	1.21
22	4.99	27.70	28.41	-2.55
23	6.31	19.85	20.63	-3.96
24	7.99	13.68	14.88	-8.78

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	P 3	T 1	T 2
P 1	0.22				
P 2	0.12	0.10			
P 3	-0.03	-0.01	0.09		
T 1	-0.21	-0.13	0.04	0.24	
T 2	0.01	0.01	-0.02	0.02	0.90

HR-3



10^4
1000
100
10
1
APPARENT RESISTIVITY (ohm-m)
0.01
0.1
1
10
100
TIME (ms)
0
50
100
150
200
250
300
Depth (m)
1
10
100
1000
10^4
RESISTIVITY (ohm-m)

DATA SET: HR-3

CLIENT: TNWR
LOCATION: Haleakala Ranch Property
COUNTY: Maui
PROJECT: Betsil Brothers Construction
LOOP SIZE: 152.000 m by 152.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: E: 3.0000 N: 100.0000 SLOPE: NONE

DATE: 06-17-03
SOUNDING: 3
ELEVATION: 177.00 m
EQUIPMENT: Geonics PROTEM
AZIMUTH:
TIME CONSTANT: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 4.043 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			177.0	580.6	
1	21.29	7.94	169.0	554.7	0.373
2	1235.7	201.5	-32.47	-106.5	0.163
3	3.18				

ALL PARAMETERS ARE FREE

CURRENT: 19.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 1 RAMP TIME: 125.00 muSEC

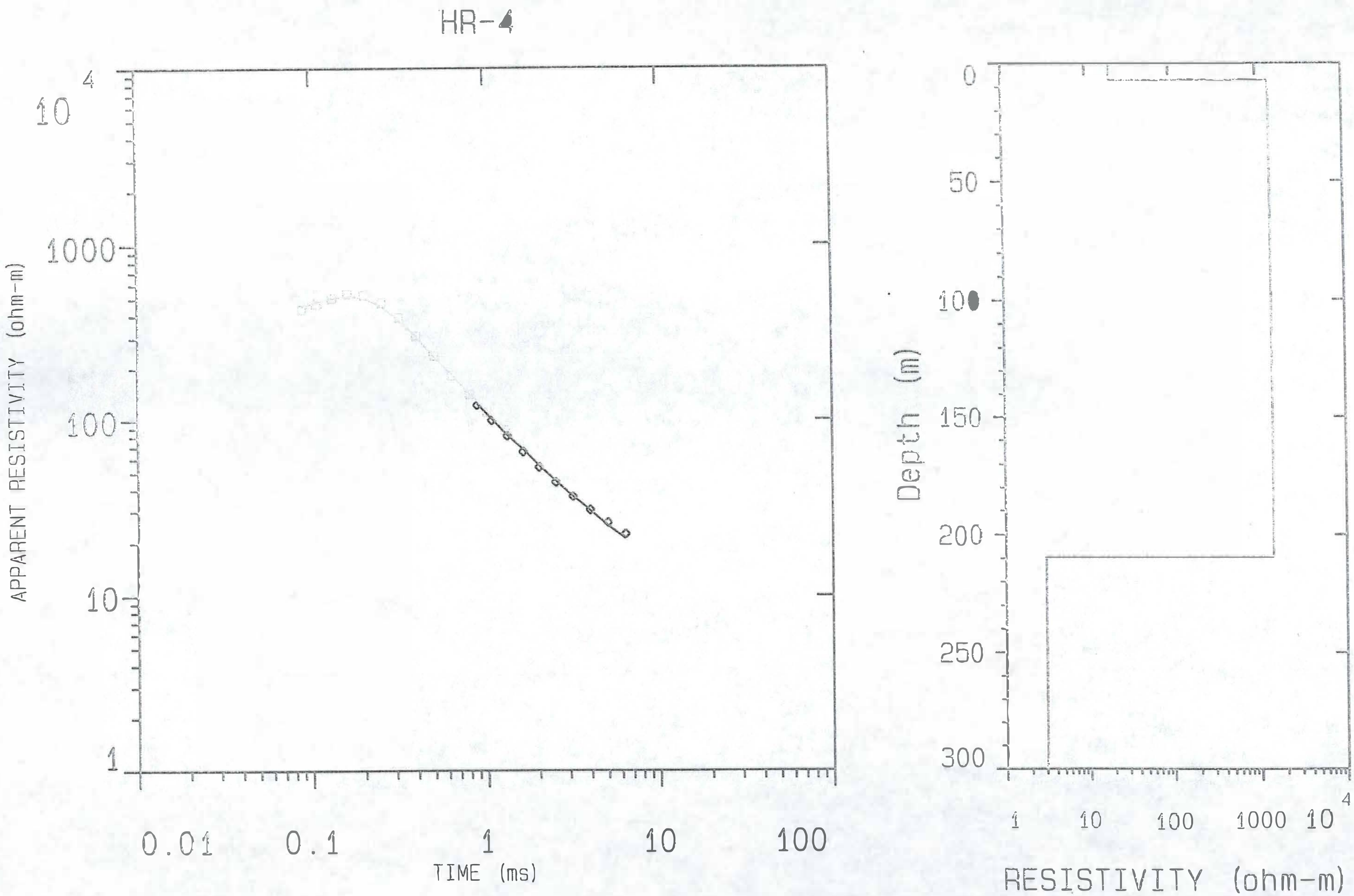
No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0881	12091.7	11645.1	3.69
2	0.106	6897.9	6689.5	3.02
3	0.131	3721.2	3644.3	2.06
4	0.161	2005.3	2084.6	-3.95
5	0.200	1148.9	1218.2	-6.03
6	0.250	733.8	796.2	-8.49
7	0.314	537.6	567.3	-5.51
8	0.395	426.0	445.8	-4.63
9	0.499	347.7	348.2	-0.146
10	0.631	287.2	291.4	-1.43
11	0.799	233.2	223.4	4.20
12	1.01	185.4	183.8	0.887
13	1.28	144.7	137.2	5.23

CURRENT: 19.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 125.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	0.881	226.5	223.0	1.52
15	1.06	188.3	186.8	0.812
16	1.31	154.6	148.6	3.91
17	1.61	124.7	120.5	3.32
18	2.00	98.83	95.01	3.87
19	2.50	76.29	74.58	2.24
20	3.14	57.31	56.62	1.21
21	3.95	42.58	42.87	-0.692
22	4.99	30.29	31.24	-3.14
23	6.31	21.19	22.82	-7.70

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	P 3	T 1	T 2
P 1	0.84				
P 2	0.06	0.06			
P 3	0.02	-0.04	0.80		
T 1	-0.15	-0.06	0.03	0.84	
T 2	0.01	0.01	0.00	0.01	1.00


HR-4
APPARENT RESISTIVITY (ohm-m)
TIME (ms)
0.01
0.1
1
10
100
1000
Depth (m)
0
50
100
150
200
250
300
RESISTIVITY (ohm-m)
1
10
100
1000

DATA SET: HR-4

CLIENT: TNWR
LOCATION: Haleakala Ranch Property
COUNTY: Maui
PROJECT: Betsil Brothers Construction
LOOP SIZE: 152.000 m by 152.000 m
COIL LOC: 0.000 m (X), 0.000 m (Y)
SOUNDING COORDINATES: E: 4.0000 N: 100.0000 SLOPE: NONE

DATE: 06-17-03
SOUNDING: 4
ELEVATION: 178.00 m
EQUIPMENT: Geonics PROTEM
AZIMUTH:
TIME CONSTANT: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 4.322 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(ft)	CONDUCTANCE (Siemens)
			178.0	584.0	
1	19.91	7.01	170.9	560.7	0.352
2	1418.7	202.5	-31.60	-103.7	0.142
3	3.04				

ALL PARAMETERS ARE FREE

CURRENT: 19.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 3 RAMP TIME: 125.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.0881	10460.6	9849.6	5.84
2	0.106	5827.9	5601.7	3.88
3	0.131	3105.9	3124.8	-0.609
4	0.161	1696.0	1762.4	-3.91
5	0.200	1009.4	1083.2	-7.30
6	0.250	674.0	723.9	-7.40
7	0.314	512.6	540.9	-5.53
8	0.395	413.8	419.4	-1.36
9	0.499	340.9	348.7	-2.28
10	0.631	283.0	273.9	3.22
11	0.799	230.1	228.6	0.653
12	1.01	183.1	175.5	4.13
13	1.28	143.7	141.8	1.36

CURRENT: 19.00 AMPS EM-58 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 125.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
14	0.881	226.2	219.1	3.15
15	1.06	189.9	183.9	3.15
16	1.31	155.1	152.3	1.82
17	1.61	125.1	119.0	4.86
18	2.00	98.68	95.64	3.08
19	2.50	76.43	74.14	2.99
20	3.14	57.54	57.28	0.465
21	3.95	42.43	42.76	-0.762
22	4.99	30.17	31.93	-5.81
23	6.31	20.97	22.89	-9.14

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	P 3	T 1	T 2
P 1	0.88				
P 2	0.06	0.04			
P 3	0.02	-0.05	0.78		
T 1	-0.11	-0.04	0.03	0.89	
T 2	0.00	0.01	0.00	0.00	1.00